Pathways of adaptive capacity for climate impact research

von
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Abstract

Climate change is already affecting societies worldwide, with the human fingerprint increasingly apparent in climate events that are emerging against the background of natural variability. Urgent and stringent mitigation of greenhouse gas emissions is instrumental for reducing risks of intensifying climate hazards, but preserving human livelihoods, economies and non-human ecosystems will also require a level of adaptation to slow-onset hazards such as sea-level rise and extreme events such as droughts, floods and heatwaves. Adaptation can substantially reduce the negative impacts of climate change, but will require large financial, institutional, human and socio-economic other resources. Quantitative estimates of future climate impacts so far mainly rely on stylized representations of adaptation, where either no adaptation takes place, or it is carried out optimally. Such representations disregard global inequalities in socio-economic conditions, which will be decisive for the systems' actual ability to deploy many of the adaptation measures. To better ascertain the degree of adaptation that can be expected based on economic, financial, technological and other capacities, projections of climate impacts and the ensuing loss and damage should account for the co-evolution between climate hazards and socio-economic development. To this end, this thesis connects several areas of climate change science to offer a toolkit for improving the representation of adaptation in quantitative modeling tools. The approach shown here embeds the socio-economic barriers to adaptation identified in the Fifth Assessment Report of the Intergovernmental Panel for Climate Change (IPCC) into the scenario framework of Shared Socioeconomic Pathways (SSPs) to – for the first time – establish quantitative pathways of adaptive capacity. Integrating adaptive capacity in the scenario space opens opportunities for a more nuanced operationalization of adaptation in quantitative modeling. In the first half of the thesis, two extensions of the scenario framework are presented, focusing on indicators of governance and gender equality as two of the key barriers to adaptation that have not yet been part of the set of indicators in the SSPs. Future trajectories of governance and gender equality explored in the first two chapters show that decades might be needed to improve adaptive capacity even in the best-case scenarios of socio-economic development, particularly in less developed countries. The scenario-dependent timelines of overcoming different socio-economic barriers suggest that high levels of adaptation might be unattainable without addressing multiple development objectives in conjunction. The second half of the thesis showcases two sectoral applications of adaptive capacity for the health and agriculture sectors, demonstrating the relationship between socio-economic conditions and differential vulnerability to possible climate stressors. The two applications serve as an entry point for accounting for adaptive capacity in estimates of future climate impacts such as heat stress and crop yield changes and provide insights for policy-making in the field of adaptation planning. Together, chapters of the thesis underscore the importance of considering adaptive capacity in expectations of future adaptation and the resulting climate impacts. The toolkit presented here is primarily suited for use in quantitative assessments of impacts and alternative policy options to incorporate adaptation-relevant information, with the ultimate goal of a more robust representation of climate change under different socio-economic development scenarios.

Zusammenfassung

Die Folgen des Klimawandels sind für Gesellschaften auf der ganzen Welt deutlich spürbar. Eine entschlossene Minderung der Treibhausgasemissionen in den nächsten Dekaden ist entscheidend für die Verringerung des Risikos sich verschärfender Klimagefahren. Gleichzeitig zeigen die Folgen des Klimawandels bereits heute, dass der Erhalt der menschlichen Lebensgrundlagen, und Ökosysteme darüber hinaus auch dringende Klimaanpassungsmaßnahmen erfordert. Anpassung bedarf es dabei sowohl für langsam einsetzenden Gefahren wie dem Anstieg des Meeresspiegels als auch für extreme Ereignisse wie Dürren, Überschwemmungen und Hitzewellen. Erfolgreiche Klimaanpassung kann die negativen Auswirkungen des Klimawandels erheblich reduzieren, erfordert aber gleichzeitig große finanzielle, institutionelle, soziale und andere Ressourcen. Quantitative Abschätzungen zukünftiger Klimafolgen beruhen bisher vor allem auf stilisierten Darstellungen von Anpassung, bei denen entweder keine Anpassung stattfindet oder sie optimal umgesetzt wird. Solche Darstellungen lassen globale Ungleichheiten in den sozioökonomischen Bedingungen außer Acht, die für die tatsächliche Befähigung diese Anpassungsmaßnahmen umzusetzen entscheidend sind. Um das zu erwartende Ausmaß der Anpassung auf der Basis wirtschaftlicher, finanzieller, technologischer und anderer Kapazitäten besser bestimmen zu können, sollten Projektionen der Klimafolgen und der daraus resultierenden Verluste und Schäden die Ko-Evolution zwischen Klimagefahren und sozioökonomischer Entwicklung berücksichtigen. Diese vorliegende Promotion leistet diesen interdisziplinären Brückenschlag und verbindet mehrere Bereiche der Klimawissenschaft zur Entwicklung eines Toolkits zur Verbesserung der Darstellung von Anpassung in quantitativen Klimafolgenmodellen. Der hier gezeigte Ansatz bettet die im Fünften Sachstandsbericht des Weltklimarats (IPCC) identifizierten sozioökonomischen Barrieren der Anpassung in den Szenariorahmen der Shared Socioeconomic Pathways (SSPs) ein, um - zum ersten Mal - quantitative Pfade der Anpassungsfähigkeit zu erstellen. Die Integration der Anpassungskapazität in den Szenarienraum eröffnet Möglichkeiten für eine nuanciertere Operationalisierung von Anpassung in der quantitativen Modellierung. In der ersten Hälfte der Arbeit werden zwei Erweiterungen des Szenariorahmens vorgestellt, die sich auf Indikatoren für Governance und Geschlechtergleichheit konzentrieren - zwei der wichtigsten Barrieren für Anpassung, die bisher nicht Teil des Indikatorensatzes in den SSPs

waren. Die in den ersten beiden Kapiteln untersuchten zukünftigen Trajektorien von Governance und Geschlechtergleichheit zeigen, dass selbst in den Best-Case-Szenarien der sozioökonomischen Entwicklung Jahrzehnte benötigt werden könnten, um die Anpassungsfähigkeit insbesondere in weniger entwickelten Ländern zu verbessern. Die szenarienabhängigen Zeitskalen für die Überwindung verschiedener sozioökonomischer Barrieren legen nahe, dass ein hohes Anpassungsniveau an Klimawandelfolgen ohne die gleichzeitige Verfolgung mehrerer Entwicklungsziele unerreichbar sein könnte. In der zweiten Hälfte der Arbeit werden zwei sektorale Anwendungen der Anpassungskapazität-Toolbox für die Sektoren Gesundheit und Landwirtschaft vorgestellt, die den Zusammenhang zwischen sozioökonomischen Bedingungen und der unterschiedlichen Verwundbarkeit gegenüber möglichen Klimastressoren aufzeigen. Die beiden Anwendungen dienen als Ausgangspunkt für die Berücksichtigung der Anpassungsfähigkeit bei der Abschätzung zukünftiger Klimaauswirkungen wie Hitzestress und Änderungen der Ernteerträge und liefern Erkenntnisse für die politische Entscheidungsfindung im Bereich der Anpassungsplanung. Zusammengenommen unterstreichen die Kapitel der Arbeit die Wichtigkeit der Berücksichtigung der Anpassungsfähigkeit bei der Erwartung zukünftiger Anpassungen und den daraus resultierenden Klimafolgen. Das hier vorgestellte Toolkit ist in erster Linie für den Einsatz in quantitativen Abschätzungen von Auswirkungen und alternativen Politikoptionen geeignet, um anpassungsrelevante Informationen mit dem Ziel einer robusteren Darstellung des Klimawandels unter verschiedenen Szenarien der sozioökonomischen Entwicklung einzubeziehen.

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Glossary

Adaptation: . . . . . The process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities.

Adaptation barriers: Factors that make it harder to plan and implement adaptation actions or that restrict options.

Adaptive capacity: . The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.

Adaptation limits: . The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.

Exposure: . . . . The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected by a climatic event.

Hazard: . . . . The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.

Impacts: . . . . The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability. Impacts generally refer to effects on lives; livelihoods; health and well-being; ecosystems and species; economic, social and cultural assets; services; and infrastructure.

Mitigation: . . . . . . A human intervention to reduce emissions or enhance the sinks of greenhouse gases.

Pathways: . . . . . . The temporal evolution of natural and/or human systems towards a future state. Pathway concepts range from sets of quantitative and qualitative scenarios or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals. Pathway approaches typically focus on biophysical, techno-economic, and/or socio-behavioural trajectories.

Risk: . . . . The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence.

Scenario: . . . . A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

Vulnerability: . . . . The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Source: IPCC, 2018. Annex I: Glossary. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)).

1 Introduction

1.1 Adaptation in the climate change risk framework

Events attributable to climate change are being detected at the present-day level of global warming of about 1.1°C above the pre-industrial period (King, Black, et al. 2016; Herring et al. 2018; Otto et al. 2020). As a result of unabated greenhouse gas emissions and current rates of warming, the global mean temperature is rising by about 0.2°C per decade (IPCC 2018), which causes more pronounced sea-level rise, heat, floods, droughts and other manifestations of climate change (Nauels et al. 2019; Dottori et al. 2018; Schleussner, Deryng, et al. 2018; IPCC 2018). Both the slow onset and the extreme events threaten livelihoods and economies around the world, particularly in the tropical regions (Schleussner, Lissner, et al. 2016; King and Harrington 2018).

Risks of negative impacts of climate change on human and other ecosystems fundamentally depend on three factors: hazard (physical manifestations of climate change), exposure (population, ecosystems and assets exposed to hazards) and vulnerability (propensity of the exposed system to be negatively affected by the hazard) (Field et al. 2014; Mechler et al. 2019, see Glossary). The hazard component is a function of the higher temperature and increases in frequency and/or intensity with every increment of warming (Hoegh-Guldberg et al. 2018). Reducing hazards - as the physical manifestation of climate change - therefore predominantly depends on the mitigation of greenhouse gas emissions. The exposure and vulnerability components, on the other hand, depend on a broad range of socio-economic factors that define the likelihood of a system being negatively affected by hazards. As such, they are shaped by uneven development processes and are often intersections of multiple socio-economic inequalities (Field et al. 2014).

Risks of climate change are unevenly distributed around the world, with many developing and least developed countries bearing disproportionately high levels of exposure and vulnerability. Projections of increasing likelihood and intensity of climate hazards already in the near term, and the identification of areas that will be most affected (Byers et al. 2018; Schleussner, Deryng, et al. 2018) stress the need for adaptation, in addition to mitigation, as a necessary strategy to safeguard livelihoods. Together with a continuously growing body of science, adaptation has been elevated in the national and international climate policy arenas, and is also enshrined in Article 7 of the Paris Agreement as a means to strengthen the global response to climate change (UNFCCC 2015).

Adaptation is defined as "the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC 2014, see Glossary). High levels of adaptation could, for instance, in Africa and Central and South America, halve the current estimate of risks of negative climate impacts on crop productivity, curtail the spread of water-borne diseases; in Europe reduce risks of economic losses from floods by more than a half; in North America reduce risks of heat-related mortality by more than a half (Field et al. 2014). In extremely vulnerable places such as the Small Islands Developing States, a high level of adaptation could reduce the risks of impacts such as loss of livelihoods from inundation by about a third, which is significant but lower than the potential of adaptation in other world regions (Field et al. 2014). On the one hand, this means the risks of climate change can by no means be avoided by adaptation alone and that fast and stringent mitigation is still a sine qua non. But, on the other hand, these examples and many more are a clear signal that adaptation can substantially reduce risks in all world regions, though with notable differences in its risk-reducing potential.

Estimates of the global costs of adaptation are currently in the range of 70 billion US dollars annually, expecting to reaching 140–300 billion US dollars in 2030 and 280–500 billion US dollars in 2050 (UNEP 2016). Global costs of adaptation are estimated to be multiple times smaller than the costs of avoided impacts (Global Commission on Adaptation 2019), while a failure to adapt will substantially increase the costs (Gawith et al. 2020). In this context, it is important to note that adaptation needs are unevenly distributed around the world, and so are the vulnerabilities and the capacities to fulfill them. Costs of adaptation, relative to GDP, are higher for low-income countries (Chapagain et al. 2020). In addition to the uneven financing capacity, countries around the world differ in capacities based on governance, human capacity and other socio-economic factors which can be seen as the non-monetary requirements for adaptation.

In other words, whether and to what extent vulnerability and exposure can be reduced by adaptation depends on adaptive capacity, defined as "the ability of a system to adjust to climate change to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (IPCC 2014, see Glossary). Adaptive capacity is a function of financial, economic, institutional and other socio-economic factors, which are not only unevenly distributed around the world but also change over time. Adaptive capacity remains a core component of vulnerability (with the two concepts sometimes used as synonymous, as noted in Preston (2009)) within the risk framework and is crucial to understand the discrepancies between the theoretical and the practical possibilities for adaptation (Füssel and Klein 2006). Holistic estimates of climate change risks require integrated analyses of hazards, exposure and vulnerability, which account for both mitigation and adaptation as the key strategies to fight climate change itself and its impacts, with a particular focus on the socio-economic capacities to undertake efforts to reduce risks.

1.2 Adaptive capacity and adaptation barriers

Adaptation to climate change is complex, both conceptually and practically. Adaptation actions concern different actors and require different resources. They can be planned and anticipatory, which would typically involve public actors and investments (e.g., investments into the development of climate change-resistant seeds); or autonomous and responsive, mainly undertaken by private actors (e.g., a farmer changing crop varieties in response to changing rainfall patterns). Local contexts and climatic conditions define what needs to be adapted to and which actors should implement those adaptation options (Dilling et al. 2019). The portfolio of possible adaptation options has been growing (IPCC 2001; Field et al. 2014), making the assessment of adaptation costs, benefits and effectiveness increasingly challenging. Individual adaptation options that are complex and context-specific can be extremely difficult, if not impossible, to capture on the global level. In turn, this poses a challenge for modeling of climate change risks, which needs to factor in the potential to reduce the negative impacts of climate change through adaptation.

However, whether any adaptation options will be implemented depends in the first place on adaptive capacity. Indicators of socio-economic conditions used to capture the various socio-economic factors that enable or prevent a community, country or region from implementing adaptation options (Smit and Wandel 2006) can be used to understand the extent to which adaptation can be expected to take place. This approach is rooted in the capability theory of Amartya Sen and Martha Nussbaum (Sen 1999; Dilling et al. 2019), which originated in relation to the broader issues of improving socio-economic welfare, arguing that increasing individuals' social, political, financial and other capabilities are the precursor of, for example, eradicating poverty. The capability theory in the context of climate change adaptation can be applied to propose that, before an adaptation action is undertaken, actors' capabilities regarding the access to finance, education, technology, etc., need to be strengthened. The capability approach thereby offers a lens to study factors that could hinder or enable – from financial, economic, institutional, social and political perspectives – a household, community or a country to adapt, and help identify areas that need to be strengthened and empowered as parts of comprehensive assessments of adaptation needs.

While the definition of adaptive capacity is not necessarily contested, in terms of its focus on a system's ability to adjust, factors that constitute adaptive capacity have been identified in a broad and fragmented field of research. More than 150 indicators of adaptive capacity have been found in a recent literature review of studies across different geographical and sectoral scales (Siders 2019). The vast number of indicators aligns with earlier notions that adaptation needs are context-dependent and need a broad range of actors involved in its implementation, and they too vary between locations.

Conceptualization of adaptive capacity in this thesis is based on the presence (or absence) of socio-economic barriers to adaptation - defined as "factors that make it harder to plan and implement adaptation actions or that restrict options" (IPCC 2014, see Glossary). Theoretically, overcoming barriers builds adaptive capacity. The absence of barriers, therefore, would signal high adaptive capacity and vice versa.

The conceptualization is made complicated by the numerous factors that have been identified as barriers to adaptation in academic and grey literature. Similar to adaptive capacity indicators, barriers comprise a "seemingly endless" list (Biesbroek et al. 2013, pp. 1119). However, there are no clear indicators nor a systematic way to assess adaptation barriers, although attempts have been made to create frameworks to identify them (Moser and Ekstrom 2010). Identified barriers are often context-specific and the research field is highly fragmented, making comprehensive assessments additionally difficult (Biesbroek et al. 2013).

The categorization of adaptation barriers in this thesis is based on the Fifth Assessment Report (AR5) of the Intergovernmental Panel for Climate Change (IPCC) – the world's largest synthesis of scientific knowledge on climate change. Tables 1.1 and 1.2 show the regional and the sectoral distributions of adaptation barriers identified in the literature included in the Chapter 16 on "Adaptation opportunities, barriers and limits" of the IPCC Working Group II (Klein et al.

Table 1.1: Classification of adaptation barriers by sector. The amount of evidence is represented by a dot (one dot for relatively little and two dots for relatively ample evidence). The cell is blank for complete lack of evidence. Since socio-economic barriers are the focus of this thesis, biological and physical barriers are excluded from the table. Source: adapted from Table 16-3 of the Chapter 16 of the AR5 (IPCC, 2014).

	barriers					
Sector	Economic	Financial	Governance	Information	Human capacity	Socio-cultural
Freshwater	•	• •	• •	• •	•	•
Terrerstrial		•	•	•		
Coastal	•	•	• •	•		• •
Ocean systems		•		•		
Food systems	• •	• •		• •		•
Urban areas	• •	• •	• •	• •	• •	• •
Rural areas	•	•	•	•		•
Human health		•	•	•		•
Human security	•	•	• •	• •		• •

2014). The synthesis of literature as shown in the tables was the state-of-the-art at the time of publishing the AR5. The descriptions of each category of barriers below follow the categorization of the AR5 but are complemented with scientific evidence that has become available since the report was published in 2014.

1.2.1 Economic barriers

While economic and financial barriers to adaptation are sometimes used interchangeably, the AR5 draws a distinction between them, regarding economic barriers in the broader context of (macro)economic development and sectoral compositions of economies which might affect their adaptive capacity. Based on the scientific evidence, there is "very high confidence"[1] that both long-term trends and short-term

[1] In the IPCC language, very high confidence is assigned to statements that are products of high agreement and robust evidence.

Table 1.2: Classification of adaptation barriers by region. The amount of evidence is represented by a dot (one dot for relatively little and two dots for relatively ample evidence). The cell is blank for complete lack of evidence. Since socio-economic barriers are the focus of this thesis, biological and physical barriers are excluded from the table. Source: adapted from Table 16-3 of the Chapter 16 of the AR5 (IPCC, 2014).

	barriers					
Region	Economic	Financial	Governance	Information	Human capacity	Socio-cultural
Africa	•	• •	• •	• •	• •	• •
Europe			• •	• •		•
Asia		•	• •			•
Australasia		•	• •	• •	•	• •
North America		• •	• •	• •	•	
Central and South America	•	•	• •	• •	• •	•
Polar Regions			•	•		• •
Small Islands	•	• •	• •	• •	•	• •
Open oceans			• •	• •		

dynamics of economic development are linked to the adaptive capacity through various channels.

Firstly, adaptive capacity can be affected through multiple climate stressors while also experiencing local and/or global macroeconomic disruptions. Studying the “double exposure” of an economic downturn and climate change has shown ways to spread risk and vulnerability over space and time and that these interconnections need to be taken into account when planning a response (Leichenko et al. 2010). The current Covid-19 pandemic is the most recent example of a health and an economic crisis that can exert massive disruptions to the function of economic systems. A crisis of this kind disrupts economic activity, increases unemployment and pushes even more people into poverty and creates unsustainable levels of debt. Governments might reprioritize their core economic issues at the expense of efforts to curb climate change unless the crises are tackled simultaneously. In the specific example, the direction of the economic recovery is still unclear, and international cooperation will be key to support climate-vulnerable countries in spurring an economic recovery that is also climate-resilient (Andrijevic, Schleussner, et al. 2020).

Secondly, economic adaptive capacity will be affected by the sectoral composition of the economy and the extent to which it relies on climate-sensitive sectors such as agriculture, forestry, fisheries and/or tourism. While these sectors are present in countries across the spectrum of income levels, developing and least developed countries remain more reliant on the primary sectors whose productivity will be affected by both slow-onset and extreme manifestations of climate change (World Bank 2021; Schlenker and Lobell 2010; Müller et al. 2011). Similarly, areas where tourism is the largest contributor to economic growth will also be disproportionately exposed to the potential impacts of climate change (Scott et al. 2019).

1.2.2 Financial barriers

Lack of financial resources and financial instruments such as loans or insurance often emerges as a key determinant of adaptive capacity. Financial barriers are present across all sectors affected by climate change. Although they tend to be more pronounced in developing countries (e.g., Chepkoech et al. 2020; Harvey et al. 2014), case studies from Europe and North America also point to the lack of access to financial capital in some instances despite their presumed high financial capacity (e.g., Biesbroek et al. 2013; Williges et al. 2017). The range of costs of adaptation options and consequently the financial capacity they require varies widely, from a relatively high cost of, e.g., building a sea wall, to a relatively small cost of, e.g., installing an air conditioning device. In addition, the pertinence of the constraint will also depend on the financial capacity of the actor who is expected to bear these costs. It has been shown that on the individual level, income is positively associated with better disaster preparedness and coping with extreme events (Toya and Skidmore 2007). The relevance of financial barriers and mechanisms to overcome them is expected to increase further with adaptation's growing costs (UNEP 2020).

Lack of financial resources often needs to be considered in conjunction with other barriers. On the one hand, lack of finance can reinforce other barriers such as access to information or improving institutional capacity which need to be improved first (Eisenack et al. 2014). On the other hand, corruption-ridden institutional setting could misuse financial capital and render the financial resources ineffective for deploying adaptation or a development strategy (Mahmud and Prowse 2012).

1.2.3 Human resources barriers

Coping with climate impacts requires substantial human resources for increasing awareness and information dissemination of adaptation options and use of climate services. They are important for leadership and policy planning of adaptation implementation, research and innovation, use of technology, diversification of economic portfolios towards more climate-resilient sectors.

In a recent review, Feinstein and Mach (2020) identify three roles of education – as one of the key dimensions of human capacity – for climate change adaptation: (1) protecting and investing in education infrastructure to reduce exposure to climate hazards and to empower educators to strengthen educational outcomes; (2) improving general education in terms of literacy, school attendance and educational attainment and (3) adaptation learning support to increase capacity to prepare for and learn from climate impacts.

A large body of research suggests that a better-educated population is less vulnerable to extreme events (e.g., Muttarak and Pothisiri 2013; Hoffmann and Blecha 2020; Pichler and Striessnig 2013). Similarly, more educated households were more likely to use adaptive techniques in agriculture and adopt new cultivation strategies (Wouterse 2017; Di Falco et al. 2011). In the longer run, higher education is associated with higher climate change resilience (Frankenberg et al. 2013) but also indirectly contributes to adaptive capacity through economic development and health (Lutz, Muttarak, et al. 2014).

1.2.4 Governance barriers

Governance and institutional capacities have been identified as an adaptation constraint present in all regions and all, but two sectors covered in AR5, which places it in the ranks of financial and information barriers as the most cross-cutting. It has also been identified elsewhere in the literature as the most frequently reported adaptation barrier (Biesbroek et al. 2013; de Coninck et al. 2018).

Implementation of policies, mobilization of resources, coordinating efforts and decision making are factors that may enable or constrain adaptation and hinge on the quality and efficacy of institutions (Klein et al. 2014; Berkhout 2012). For example, institutional quality is associated with adopting environmental policies (Dasgupta and De Cian 2018), and better governance has also been shown conducive to receiving adaptation aid from donors (Weiler et al. 2018). On the other side, inept governance can hinder the ability to fulfill adaptation goals (Berrang-Ford, Biesbroek, et al. 2019). The level of corruption has been shown as particularly relevant for adaptation (Lesnikowski, Ford, Berrang-Ford, Barrera, Heymann, et al. 2015; Berrang-Ford, Ford, et al. 2014) because it weakens institutions, damages public trust, diverts funds from budgets and investment and can lead to a misuse of funds intended for adaptation or post-disaster operations (Mahmud and Prowse 2012).

Given that governance is identified as one of the most prominent barriers to adaptation, it is an indispensable dimension of adaptive capacity. For this reason, Chapter 2 expands the SSP scenario set with a quantitative indicator of governance, building on the relevant literature and thereby filling an important knowledge gap.

1.2.5 Social and cultural factors

A large collection of literature in the AR5 emphasizes the role of social and cultural factors in perceptions of risk, consideration of adaptation options among different actors and distribution of vulnerability influenced by factors such as gender, age, social status, ethnicity, religion and culture (Moser and Ekstrom 2010; O'Brien and Wolf 2010; Adger, Quinn, et al. 2012). Numerous case studies have identified context-dependent mechanisms through which socio-cultural factors can hinder adaptive capacity, contributing to the complexity of this interaction (Adger, Dessai, et al. 2009). In addition, the difficulty of quantifying these factors makes their comparison and modeling a daunting task.

For example, Nielsen and Reenberg (2010) studied the uptake of adaptation in the form of livelihood diversification in an in-depth analysis of a village in Burkina Faso, showing that different cultural values enabled one and prevented another group from adapting. Another study of Swedish foresters showed that their adaptation actions were dependent on their belief about climate change (Blennow and Persson 2009).

Gender inequality has been identified as an important constraint to adaptation. Women's adaptive capacity could also be limited by cultural norms and entrenched social structures, which are reflected in work divisions, norms around mobility and decision-making, and access to financial and information resources (Rao et al. 2018; Rao 2017; Alston 2013; Pearse 2017). This is the focus of Chapter 3 which expands the SSPs with an indicator of gender inequality. Lifting the knowledge from specific case studies to the level of global pathways closes an important gap in the current literature.

1.2.6 Information, awareness and technology

Lack of information and technology are also identified as some of the most common adaptation barriers. Knowledge gaps about potential climate impacts and adaptation options are observed in developing and developed countries alike (Biesbroek et al. 2013; Thaler et al. 2019; Piggott-McKellar et al. 2019; Antwi-Agyei et al. 2015), though they can differ in severity (Lehmann et al. 2015). Misperception of risk of climate change or overconfidence in the ability to deal with it can result in the insufficient or complete absence of adaptation planning and implementation (Monirul Islam et al. 2014; Kuruppu and Liverman 2011). On the flip side, information on potential risks of storms, droughts or heatwaves, prioritization and planning to prepare for them can greatly reduce vulnerability (Lutz, Muttarak, et al. 2014; Street et al. 2019). Access to and deployment of technology for adaptation is also often identified as an important dimension of adaptive capacity (McNamara and Buggy 2017; Lybbert and Sumner 2012). Furthermore, awareness and access to information and knowledge transfer can be crucial in its potential implementation (Biagini et al. 2014).

Information and technological barriers often need to be considered together with other barriers. For example, finance might play a decisive role in developing, accessing and deploying technologies (Bryan et al. 2009). Or, as found in a recent study, implementation of adaptation (in this case irrigation) largely failed due to weak governance, despite having access to both finance and technology (Higginbottom et al. 2021).

1.3 Problem definition

Since the Third Assessment Report of the IPCC, adaptation is prominently featured in Assessment Reports as a strategy to reduce the risk of climate change across different world regions and sectors. Figure 1.1, from the Summary for Policymakers for the AR5 (Field et al. 2014), showcases climate change risks and possibilities to reduce them through adaptation. The Figure (here cropped for brevity) focuses on the African continent for two examples of climate change risks: degradation of water resources driven by increasing temperatures and sea-level rise and reduced crop productivity, driven primarily by changes in temperature and precipitation.

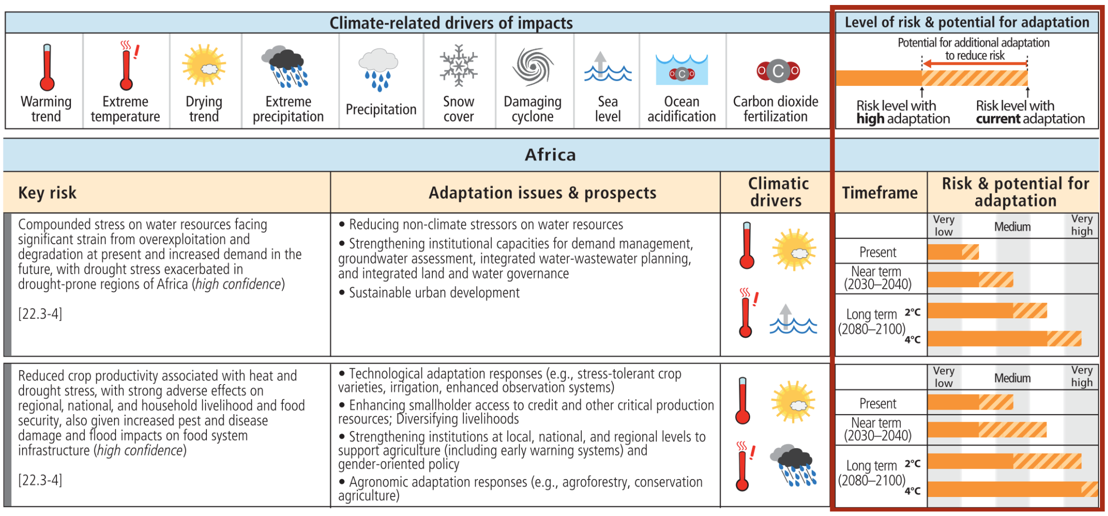

Figure 1.1: Risks from climate change in Africa and potential to reduce risks with adaptation. Source: Assessment Box SPM.2 Table 1 (IPCC, 2014).

The last column (highlighted) shows the level of risk that can be reduced by adaptation on three timeframes: current, near-term and long-term. The long-term timescale is disaggregated for two global mean temperature levels, namely 2°C and 4°C above the pre-industrial period. Risk can be reduced with two possible adaptation levels: the current and a high level, with the high level of adaptation in some cases exhibiting the potential to halve the amount of risk compared to the current adaptation. While this speaks to the need for adaptation based on its potential to reduce impacts, this kind of representation does not account for whether a given level of adaptation can actually be deployed given the socio-economic factors on which it is conditioned and therefore whether it can reasnably be expected to actually reduce the risks. In the context of adaptive capacity, adaptation deployment requires financial, human, technological and other resources, implying that a high level of adaptation would require a high level of such resources. Therefore, the stylized representation of adaptation could under- or overestimate the extent to which risks could be reduced by adaptation if the socio-economic barriers are not considered.

Another example of a binary representation of adaptation in the context of climate change risks can be found in the recent IPCC Special Report on the Ocean, Cryosphere in a Changing Climate (SROCC) (IPCC 2019). In the risk assessment of sea-level rise, adaptation has the potential to reduce impacts with a "no-to-medium response" and the "maximum potential response"[2]. While the "no-to-medium response" assumes little change from the present-day circumstances, the "maximum" response assumes a substantial reduction of risks through a combination of responses under the assumption of "minimal financial, social and political barriers" (IPCC 2019, p. 34). Similarly to the example from 1.1, such investments into protection against sea-level rise can amount to billions of dollars (Hinkel, Lincke, et al. 2014; de Coninck et al. 2018) and hence may face a range of barriers in reality, particularly in countries with limited fiscal space for undertakings of this degree.

Not accounting for heterogeneity between the world's regions, countries and communities in adaptation-relevant resources and access creates incomplete as-

[2]the word response replaces adaptation because possibilities such as planned or forced relocation, which are controversial adaptation options, are included

sessments of future risks of climate change. By failing to capture the actual potential for adaptation conditioned on socio-economic contexts, potential for adaptation could be overstated.

Quantitative research at the nexus of climate science, social science and economics, which feeds into the kinds of estimates shown in Figure 1.1 or the example of the SROCC, is not yet advanced in accounting for factors that enable or constrain adaptation in the first place, nor what the temporal evolution of those factors could look like (de Coninck et al. 2018). The socio-economic contexts are subjects to dynamic temporal changes which are important considerations of hazards, exposure vulnerability in the future. In tools such as models estimating climate change impacts or Integrated Assessment Models (IAMs) that assess ways to tackle climate change, adaptation tends to be either absent or treated in a rather stylized way (Patt et al. 2010; Holman et al. 2019). The consequence of not accounting for adaptive capacity when assuming a certain level of adaptation could underestimate climate impacts on human and other systems because the expectations of adaptation might be detached from the socio-economic realities. Overly optimistic expectations of adaptation for risk reduction could also lead to downplaying the urgency and the required level of mitigation, if adaptation would appear as a supplement to mitigation.

With the objective of advancing the understanding of future impacts of climate change as a function of adaptation, this thesis connects several fields in climate change research to deliver quantitative pathways of adaptive capacity, primarily aimed at modeling tools that deal with various aspects of climate risks but do not yet systematically incorporate adaptive capacity measures. The remainder of the introductory chapter (1) reviews the representation of adaptation in modeling tools and (2) introduces the scenario set of Shared Socio-economic Pathways (SSPs) and ways to embed adaptive capacity can be within their framework to create a toolkit for assessment of adaptive capacity.

1.4 Representation of adaptation in modeling tools

Compared to mitigation, adaptation has so far been less elaborately represented in tools that help scientists study future impacts and damages caused by climate change. In general, ample differences between mitigation and adaptation contribute to this discrepancy in representation. Mitigation is oriented towards a global goal (i.e., keeping the global mean temperature increase in line with the targets of 1.5°C or well below 2°C compared to the pre-industrial period). Metrics to assess the progress towards that goal are rather straightforward (e.g., the amount of reduced greenhouse gas emissions). For adaptation, on the other hand, both the goal and the metric are much more difficult to define because adaptation tends to be context-specific, involve a broad range of actors, and provide local rather than global benefits. The Paris Agreement, however, has made a step in the direction of defining a global adaptation goal, calling for "enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development and ensuring an adequate adaptation response in the context of the temperature goal" (UNFCCC 2015). Tracking adaptation performance vis-a-vis a goal is more difficult compared to mitigation. However, there has been some progress on defining a framework to assess adaptation progress on the global level (UNEP 2016) and on designing concepts that could be used to compare adaptation progress between governments (Berrang-Ford, Biesbroek, et al. 2019). Still, it can be difficult to differentiate adaptation from other socio-economic development processes, which makes the estimates of cost-effectiveness more difficult (Füssel 2010). This stresses the importance of embedding the potential for adaptation in the context of socio-economic development and understanding the future trajectories of adaptive capacity contingent on the level of socio-economic development.

Independent of comparison to mitigation, adaptation with its many options, actors, scales, and interactions, makes model representation a challenging task. Nevertheless, the absence or oversimplification of adaptation in models misleads estimates of overall impacts and damages of climate change, for which reason representation of adaptation is one of the critical research needs in the modeling world (Schewe et al. 2019).

The remainder of this subchapter reviews ways in which adaptation is currently represented in some of the models widely used. The most relevant types of models in this context are Integrated Assessment Models (IAMs) and climate impact models. Though here treated separately, these models are often linked to study the effect of policy decisions on climate-related outcomes.

1.4.1 Adaptation in IAMs

Integrated assessment models (IAMs) assess policy options and impacts of climate change by combining socio-economic parameters with physical aspects of climate change (Weyant 1995). While many types of IAMs exist, in broad terms they can be separated into simple (cost-benefit) and complex (process-based) types. Most simple IAMs that incorporate adaptation do so implicitly, without modeling the process through which adaptation occurs, and assume that whenever adaptation is a cost-effective opportunity (e.g., a sea wall will be built if the climate damages exceed the cost of building a sea wall), it happens automatically (Patt et al. 2010). This does not only assume the unconditional availability of the adaptation option but to arrive to cost-benefit estimates, must also monetize the lives and homes of those affected by sea-level rise. Steps towards explicitly accounting for adaptation among the simple cost-benefit IAMs were made in models PAGE (Hope et al. 1993), and the more recent AD-DICE (De Bruin, Dellink, and Tol 2009) and its regional extension AD-RICE (De Bruin, Dellink, Agrawala, et al. 2009). However, adaptation has been criticized for being overly optimistic in PAGE (De Bruin, Dellink, and Tol 2009), while AD-DICE and AD-RICE still treat adaptation as either non-existent or applied optimally whenever it is possible.

The feature of the simple IAMs to conduct cost-benefit types of analyses of efforts to tackle climate change, the assessment of the relative effect of adaptation and mitigation on climate damages makes them appear as substitutes. For example, AD-DICE model (De Bruin, Dellink, and Tol 2009) suggests that the mitigation target can be reduced by one quarter when optimal adaptation is implemented. This is a misleading representation of the reality in which the two measures act on different spatial and temporal scales, have differential impacts on people's welfare depending on the level of exposure and vulnerability to climate impacts (Klein et al. 2014). DICE model has also been recently criticized for outdated parametrization of mitigation-relevant factors that produce misleading estimates (Hänsel et al. 2020). Optimal calibration is based on estimates of adaptation at the point at which the costs and the residual impacts are minimal. As a result, regarding them as substitutes means that adaptation investments can reduce mitigation targets, which justifies the earlier mentioned concern that adaptation could downplay the urgency of mitigation. Defining the optimal level of adaptation could lead to conclusions about the necessary level of mitigation, which could be underestimated because the damages of climate change with optimal adaptation appear lower than they would be if adaptation barriers would be incorporated into considerations of whether adaptation can be deployed.

De Bruin and Dellink (2011) included various barriers to adaptation identified in the literature in the AD-DICE08 model. While this was a valuable contribution, this approach was global and for a single point in time, while adaptation barriers differ across countries and sectors and might evolve in different trajectories. Additionally, the barriers identified by de Bruin and Dellink (2011) are unrelated from the synthesis of the IPCC reports and are disconnected from the scenario framework of the SSPs, which provide a way to harmonize scenarios across models.

Complex IAMs, on the other hand, primarily estimate greenhouse gas emissions from the interaction between population, economy, land use and energy systems. They often have linked modules that use the emissions (and the corresponding temperature increase) to estimate impacts on different sectors. Complex IAMs still vary in complexity as they represent interactions between various actors and sectors in different ways. While IAMs can provide detailed estimates on mitigation costs, adaptation is by and large absent from the current state of the art. Incorporating impacts and adaptation into complex IAMs is one of the major research frontiers in the field, though challenges such as lack of quantitative data that models could use hampers these efforts (Clarke et al. 2014). Without accounting for adaptation pathways, however, models will not reliably incorporate climate impacts or estimate economic damages, for which reason approaches to quantify adaptation are some of the highest priorities.

1.4.2 Adaptation in physical models

Impacts of climate change are modeled through models that focus on capturing the biophysical relationships between climatic conditions and, for example, land use and agricultural processes, water availability, coastal changes, etc. These relationships are, of course, complex and influenced by many biological, physical and chemical processes. But beyond those, adaptation that requires human interventions will also depend on a set of socio-economic factors (Brown et al. 2017). Physical models suffer from similar drawbacks in the treatment of adaptation as the economic models discussed above. These assumptions are similarly consequential as was the case for the IAMs: simplistic assumptions about the optimal or unconstrained uptake of adaptation lead to overly optimistic estimates of adaptation, thereby underestimating future climate impacts. Conversely, modeling exercises that do not incorporate adaptation at all can overestimate impacts (Minoli et al. 2019).

An overview of adaptation in climate impact models finds that, among the models that consider adaptation in some way, about a third does not incorporate adaptation barriers, the temporal dynamics of the barriers or the limits to the uptake of adaptation and only one-tenth of the models account for all three of those factors (Holman et al. 2019). Failing to account for barriers reinforces the assumption that adaptation will be readily available and implementable, similar to the example from the SROCC shown earlier. The overview also finds that adaptation in agricultural models is more frequently and more comprehensively represented than in water models, though largely reflecting the underlying model assumption surrounding optimization and equilibrium underlying model assumptions, rather than empirical evidence on factors that trigger adaptation.

Complex or process-based IAMs have been coupled with sectoral impact models, which is an application space for the toolkit presented here, particularly for models that already "understand" the SSP scenarios. For example, the coupling of the DIVA coastal model (Hinkel and Klein 2009) and the IMAGE IAM (Stehfest et al. 2014) to assess flooding damages (Hinkel, Vuuren, et al. 2012). Adaptation is scenario-specific to the extent that it depends on wealth, but based on a recent overview of local barriers to coastal adaptation (Hinkel, Aerts, et al. 2018) identifies additional economic, financial, technological and socio-cultural barriers that will also need to be overcome for adaptation deployment. This overview could serve as an update and used to couple the identified barriers with SSP trajectories of adaptation barriers and be used in the DIVA model of coastal adaptation.

Accounting for adaptive capacity is highly relevant for the agriculture sector, whose impact models have also been coupled with IAMs to assess crop yields under different mitigation and socio-economic scenarios (Havlik et al. 2014; Popp et al. 2014; Stehfest et al. 2014). Adaptation in these coupled models mostly happens without considering the barriers, which can be improved upon by understanding factors that constitute low or high adaptive capacity in the agricultural sector (i.e., socio-economic factors correlated with irrigation, fertilization and other crop management practices) (Schewe et al. 2019).

Similarly, coupling IAMs and impact models allows for studying the impacts of heat stress on human health and mortality, as well as ways in which heat stress interacts with energy demand for cooling. Quantifying impacts of global warming on human health is an active and policy-relevant research field and another sectoral application area for adaptive capacity indicators (Schwingshackl et al. 2021; Colelli and Cian 2020).

1.5 Methodological framework: connecting the SSPs and adaptation barriers

The SSP scenario framework (O'Neill, Kriegler, et al. 2017) is used to bridge the qualitative identifications of determinants of adaptive capacity with a quantification meaningful for IAMs and climate impact models.

Scenarios are a commonly used tool to explore uncertainty. Many models rest on assumptions that are highly uncertain, particularly those that relate to socio-economic systems which are outcomes and parts of complex dynamics. Scenarios are limited to a commonly agreed upon set in order to facilitate comparison between the modeling groups and the users of climate services that result from this research. The current state-of-the-art of the climate impacts science relies on a framework with two components: scenarios of future greenhouse gas emissions which translate into different global warming levels and scenarios of future socio-economic conditions. The two components are meant to be used in an integrated way by models to analyze the consequences of future warming levels meeting future societies.

SSPs - the socio-economic component of the scenario framework - consist of five scenarios that rest on qualitative narratives or storylines that span a broad range of plausible futures of the 21st century in terms of demographics, economic conditions, inequality, international cooperation, technological change and other socio-economic factors (O'Neill, Kriegler, et al. 2017). The five scenarios describe challenges to adaptation and mitigation that stem from alternative societal trends and they by design do not incorporate climate impacts but represent baseline conditions in the absence of climate change (Figure 1.2).

SSP1, the "Sustainability" scenario, is a future of progressive socio-economic development, with increasing investments in health and education which contribute to slower economic growth, economic growth powered by increasingly decarbonized energy systems, fast technological progress, reduced inequalities both within and between countries and increased international cooperation and management of the global commons. Objectives of economic growth shift towards well-being in

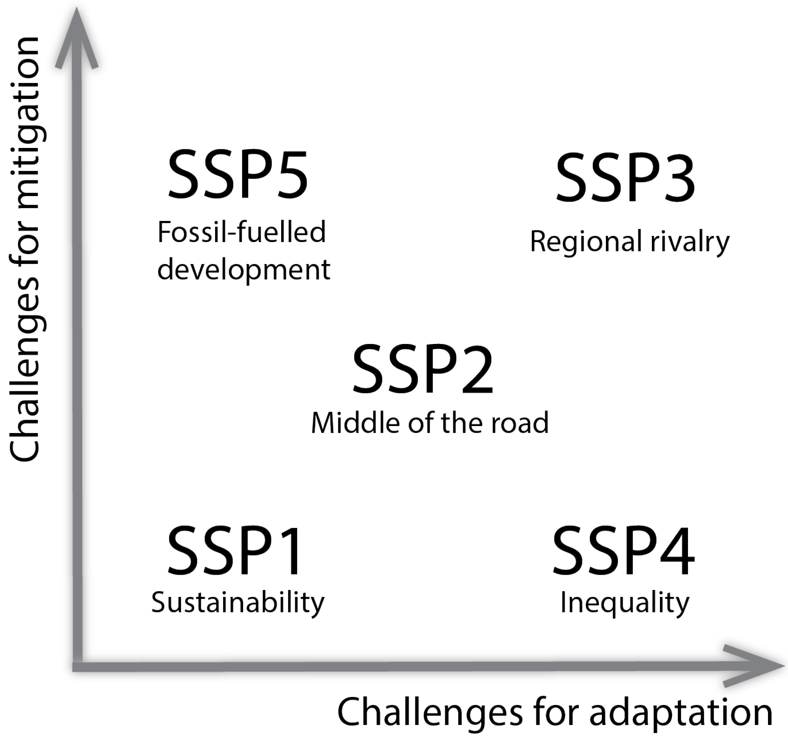

Figure 1.2: SSP scenarios assessed according to their challenges to adaptation and mitigation

developed countries, while developing countries are supported in pursuing green economic growth. Converging global development based on green energy makes this scenario exhibit low adaptation and mitigation challenges. Although none of the scenarios are actually tailored to achieve the Sustainable Development Goals (SDGs), many of the elements of SSP1 resonate with the SDG targets. The properties of the SSP2, also termed "The Middle of the Road", is a scenario of moderate challenges both for mitigation and adaptation. It is largely a continuation of historical trends, with economic growth and development happening unevenly across the world, population growth leveling off in the second half of the century with insufficient investments in education precluding more substantial progress. There is some technological progress, but without major advancements. Resource intensity of economic growth somewhat reduces, but reliance on fossil fuels remains. There is a tendency to refer to this scenario as the one closest to reality, but this does not necessarily hold and was not the intention of the scenario designers who stress that the scenario set should be used jointly.

SSP3, the so-called “Rocky road” or scenario of “regional rivalry”, describes a world where the focus shifts towards national and regional issues, trade is weakened by barriers and countries orientate towards national and regional food and energy security at the expense of development outside the region, and regional conflicts emerge. Economic growth is slow and resource-intensive, investments in education and health are reduced, while population growth is high in developing countries and low in developed. Inequalities are on the rise the and technological progress is weak. The combination of slow and unequal socio-economic progress, weak global institutions and tepid cooperation on solving problems make challenges for SSP3 high both for mitigation and adaptation to climate change.

The world of inequality in SSP4 envisages an increasing rift in socio-economic development worldwide, driven by unequal investments in education, which create disparities in economic and political opportunities. Convergence in economic growth does not happen because growth remains moderate in developed countries and sluggish in developing and low-income countries. Similarly, technological progress is substantial in rich countries while developing countries may struggle with providing necessities such as sanitation. Since wealthy countries progress towards decarbonizing their energy sectors, while a large part of the world remains at low levels of development, this scenario is characterized by low challenges to mitigation but high challenges to adaptation.

Finally, the SSP5 is the scenario of “Fossil fueled development” in which industrialization rapidly takes off worldwide, with hefty investments in innovation and education, markets become increasingly integrated and international cooperation is strong. Population growth slows down in currently high fertility countries and slightly increases due to an optimistic economic future in countries where currently birth rates are low. The attitude towards environmental problem solving is techno-optimistic, with faith in engineering solutions to climate change. For this reason, SSP5 is considered to have low challenges to adaptation but high challenges to mitigation due to its fossil-fueled economic growth.

The adaptation side of the SSPs remains under-explored compared to mitigation, although the scenarios allow for the assessing societies' abilities to adapt and adaptation pathways instead of mere assumptions that adaptation will occur (van Ruijven, Levy, et al. 2013; O'Neill, Carter, et al. 2020). The collection of papers in this thesis contributes to closing this gap with a representation of adaptive capacity within the scenario framework.

Scenario elements that describe future socio-economic development can be connected to the adaptation barriers identified in the AR5, which can be used to quantify adaptive capacity. Elements of the SSPs were quantified as part of the original scenario package and they provide country-level projections of GDP per capita (Crespo Cuaresma 2017; Dellink et al. 2017; Leimbach et al. 2017), population size and age structure (KC and Lutz 2017), educational attainment (KC and Lutz 2017) and urbanization (Jiang and O'Neill 2017). The scenarios have been expanded with projections of indicators of the Human Development Index (Crespo Cuaresma and Lutz 2015), inequality (Rao et al. 2018), conflicts (Hegre, Buhaug, et al. 2016), and two extensions that are parts of this thesis: governance (Andrijevic, Crespo Cuaresma, et al. 2020a) and gender inequality (Andrijevic, Crespo Cuaresma, et al. 2020b).

In the current form, the quantified SSP elements can be used as proxies for adaptation barriers identified in the AR5 and shown in Table 1.1 (for sectors) and Table 1.2 (for regions). For example, economic and finance dimensions can be proxied with urbanization and GDP. Information and human capacity barriers can be represented with education, population structure and HDI. Governance barriers can be proxied with a governance indicator as proposed in Chapter 2. Socio-cultural barriers can be represented by, for example, income inequality and gender inequality proposed in Chapter 3. While the AR5 adaptation barriers and the SSP dimensions do not necessarily correspond to one-on-one mapping (e.g., economic barriers such as the sectoral composition of economies are not yet part of the SSP framework), the SSP indicators are not an exhaustive set and they can be updated and supplemented with new and additional indicators.

The adaptation barriers and SSP indicators can be combined to represent the adaptive capacity for a particular adaptation option, a sector or a geographical unit. Chapters 4 and 5 illustrate how statistical regressions can be used to identify dimensions of the SSPs relevant for two adaptation options and thereby assess adaptive capacity. The next section will elaborate on why this is necessary from the perspective of modeling tools and how the current representation of adaptation or absence thereof can underestimate future climate impacts.

Timescales of adaptive capacity, in terms of barriers to adaptation and how they can be overcome, are critical for understanding adaptation. Identification of barriers in different sectors relevant for climate change adaptation, and insights into their plausible scenarios, provides a research and a policy tool to understand target areas for additional efforts needed to overcome barriers and enhance adaptive capacity to deal with climate change.

1.6 Objective and the scope of the thesis

Uncertainties surrounding adaptation's socio-economic context are an important consideration in projections of overall climate impacts and strategies to address them. This thesis integrates adaptive capacity within the scenario framework of future socio-economic pathways and thereby help explore this uncertainty space. Assessment of adaptive capacity is conceptualized through quantified barriers to adaptation identified in the literature. The "toolkit" to assess adaptive capacity presented here is primarily aimed at models that already operate with SSP scenarios, mostly complex IAMs and climate impact models. The application of this toolkit is a step forward in the representation of adaptation and subsequently climate change damages but can also be applied for any exploration of uncertainty for strategies that hinge on socio-economic factors.

The socio-economic conditions are, of course, not limited to understanding climate change adaptation but are also central to the broader development objectives, which inevitably have to be regarded in the context of climate change. Two-thirds of the world population live in countries classified as “developing” (UNCTAD 2020) and are confronting challenges such as poverty eradication and widespread provision of public goods such as health care and education. Since many of these countries will bear the brunt of climate change impacts, development needs to be considered in conjunction with adaptation to reduce the risks of impacts.

Ability to adapt will be particularly decisive for countries that are at the risk of experiencing *loss and damage*, which refers to the residual climate-induced losses and damages resulting from an inadequate capacity to adapt or exceedance of available possibilities to adapt to climate change hazards (Mechler et al. 2019). Loss and damage can mean both economic and non-economic values (i.e., items that are not traded in markets, such as human life, health, culture, heritage etc.) (Serdeczny et al. 2017). Some climate hazards might exceed hard limits where no adaptation is possible, thereby rendering loss and damage unavoidable. However, for hazards that are still manageable with adaptation options, improvements in adaptive capacity will be key to reduce loss and damage (Warner and Van Der Geest 2013). Therefore, improved asssessement of climate impacts through accounting for future pathways of building adaptive capacity can be helpful for estimating the extent of loss and damage for the most vulnerable.

The structure of the thesis is shown in Figure 1.3. Chapters 2 and 3 expand the SSPs with two additional indicators of adaptation barriers, and Chapters 4 and 5 exemplify sectoral application of the quantitative assessment of adaptive capacity. Chapter 6 synthesizes the results of Chapters 2-5, discusses their implications, limitations and suggests avenues for future research.

Chapter 2 is a study on governance in the context of adaptive capacity. Governance is the most prominently featured barrier to adaptation in the AR5 of the IPCC but quantitative assessments were so far absent from the scenario framework. The indicator of governance used here is broadly conceptualized as quality of

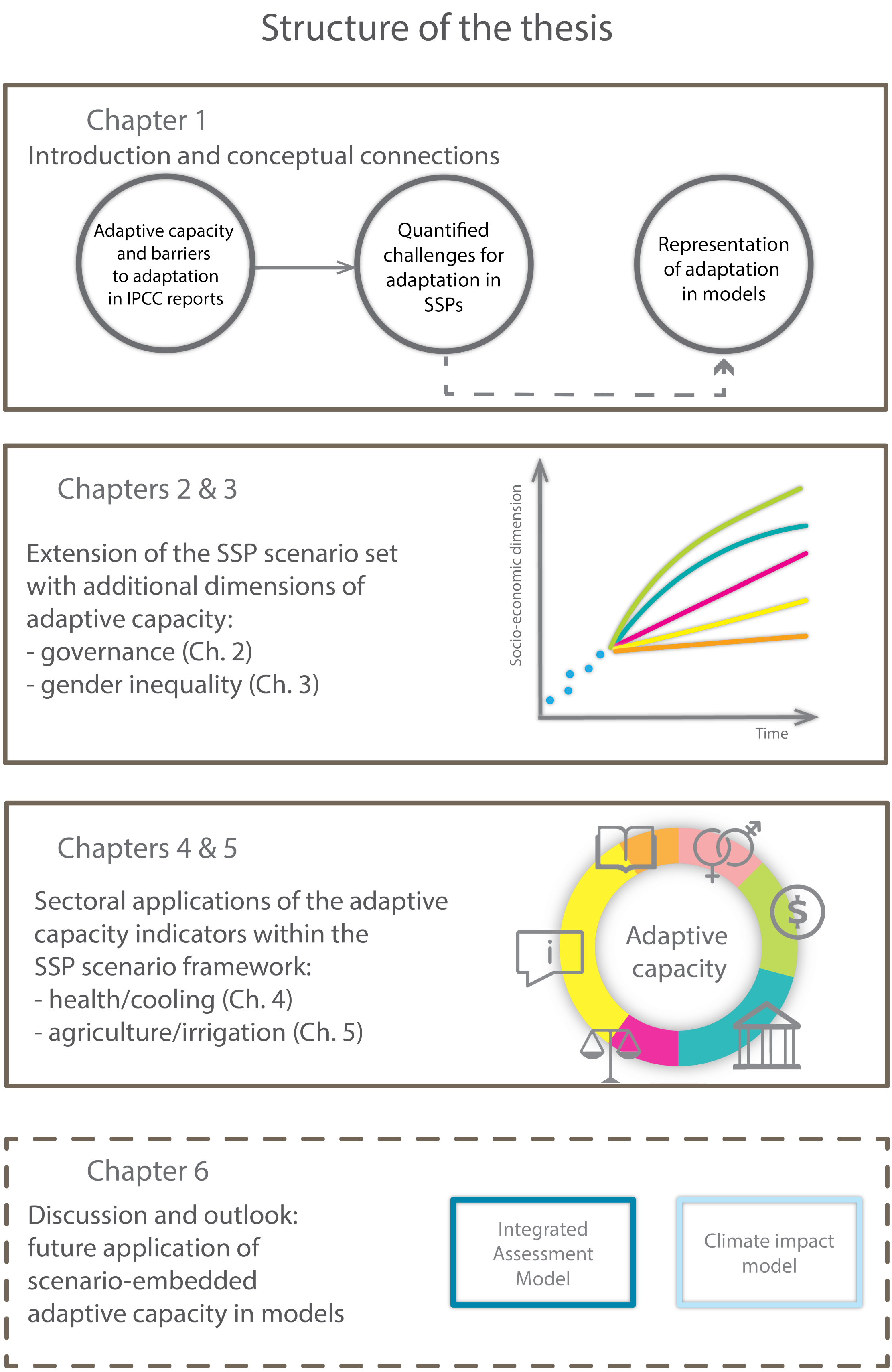

Figure 1.3: Structure of the thesis.

institutions, rule of law, control of corruption and political stability, as indispensable ingredients of adaptation planning and implementation. The study combines the multi-dimensional Worldwide Governance Indicator (Kaufmann 2010) with global panel regressions to estimate other socio-economic components that correlate with governance and uses the statistical relationship to extrapolate it in a manner that is internally consistent with the SSP scenarios.

Chapter 3 is the second extension of the SSPs, focusing on gender inequality as another key adaptation barrier and a component of adaptive capacity. A large body of literature established that women are disproportionately vulnerable to climate change. This relative position compared to men is not assumed to be a product of inherent characteristics of women that make them more vulnerable, but of social structures that deprive women of adaptive capacity in terms of finance, information, education, or through obligations to commit to house work and care for dependents, etc. The study uses the Gender Inequality Indicator (UNDP 2018) which encompasses dimensions of gender inequality in economic and political opportunities, health and education. The indicator can be meaningfully proxied as a linear combination of income, education and gender inequality in education. This relationship is subsequently used to project gender inequality along the five SSP scenarios.

Chapter 4 is the first application of the concept of adaptive capacity within the SSP framework. It uses the concept of the cooling gap, defined as the difference between the population exposed to heat stress and population with the capacity to adapt to it with the use of air conditioning. Country-level adaptive capacity in the face of heat stress is found to be a function of GDP per capita, urbanization and income inequality. The study estimates the cooling gap for the different SSPs and contributes to identification of hotspots of vulnerability around the world.

Chapter 5 is the second application of adaptive capacity. An empirically derived gap between current agricultural crop yield and the maximum potential yield based on biophysical conditions is the starting point. The gap is expressed as a Sustainable Irrigation Deployment Index (SIDI) designed for the study of this chapter. The SIDI assesses the potential to increase agricultural yields through the use of sustainable irrigation, and socio-economic factors that correlate with the SIDI are established using a simple statistical model. The governance indicator introduced in Chapter 2 – defined as the institutional capacity of countries – emerges as a socio-economic factor that best explains the current level of sustainable irrigation deployment. Future trajectories of governance are then used as predictors for the future closing of the yield gap.

1.7 Statement on contribution to the chapters of the thesis

This doctoral thesis includes two manuscripts published in peer-reviewed journals, and two manuscripts under review. I, Marina Andrijevic, declare herewith to be the lead author of three out of four chapters in this thesis. Contributions, as detailed here below, have been confirmed in writing by all co-authors.

Chapter 1 (Introduction) and Chapter 6 (Discussion and conclusion) were written by Marina Andrijevic. Dr. Sabine Fuss provided feedback on the earlier drafts of Chapters 1 and 6.

Chapter 2:

Andrijevic, Marina, Jesus Crespo Cuaresma, Raya Muttarak and Carl-Friedrich Schleussner. "Governance in socio-economic pathways and its role for future adaptive capacity". *Nature Sustainability* 3, no.1 (2020): 35-41. `https://doi.org/10.1038/s41893-019-0405-0`

M.A. and C.F.S. conceived the study. M.A. performed the analysis with the guidance of J.C.C. M.A. wrote the manuscript with contributions of all authors.

Chapter 3:

Andrijevic, Marina, Jesus Crespo Cuaresma, Tabea Lissner, Adelle Thomas and Carl-Friedrich Schleussner. "Overcoming gender inequality for climate resilient development." *Nature Communications* 11, no.1 (2020): 1-8. https://doi.org/10.1038/s41467-020-19856-w

M.A. conceived the study. M.A. performed the analysis with the guidance of J.C.C. M.A. wrote the manuscript with contributions of all authors.

Chapter 4:

Andrijevic, Marina, Edward Byers, Alessio Mastrucci, Jeroen Smits, Sabine Fuss. "Future cooling gap in Shared socio-economic Pathways". In review in *Environmental Research Letters*

M.A. conceived the study and performed the analysis with feedback from E.B. and A.M. E.B. provided the climate input data. The data on air conditioning was provided by J.S. with contributions from A.M. M.A. wrote the manuscript with contributions by all authors.

Chapter 5:

van Maanen, Nicole, **Marina Andrijevic**, Quentin Lejeune, Lorenzo Rosa, Carl-Friedrich Schleussner. "Scenarios of sustainable irrigation expansion in the 21st century". In review in *Environmental Research Letters.*

N.v.M, M.A. and C.F.S. conceived the study. N.v.M. performed the analysis with guidance from M.A. N.v.M wrote the manuscript with contributions by all authors.

2

Governance in socioeconomic pathways and its role for future adaptive capacity

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Abstract

Weak governance is one of the key obstacles for sustainable development. Undoubtedly, improvement of governance comes with a broad range of co-benefits including countries' abilities to respond to pressing global challenges such as climate change. However, beyond the qualitative acknowledgment of its importance, quantifications of future pathways of governance are still lacking. This study provides projections of future governance in line with the Shared Socio-economic Pathways (SSPs). We find that under a "rocky road" scenario, 30% of the global population would still live in countries characterized by weak governance in 2050, while under a "green road" scenario weak governance would almost be entirely overcome over the same time frame. Based on pathways for governance, we estimate the adaptive capacity of countries to climate change. Limits to adaptive capacity exist even under optimistic pathways beyond mid-century. Our findings underscore the importance of accounting for governance in assessments of climate change impacts.

2.1 Introduction

Future societies' resilience against global challenges such as climate change hinges upon successful implementation of policies, actions and development strategies (IPCC 2018). Those actions need to be facilitated by the quality and efficiency of governance, which makes governance an essential ingredient for assessing countries future climate vulnerability and coping capacity (Klein et al. 2014). More broadly, institutions and governance are key determinants of long-term stability and sustainable growth of nations (Acemoglu and Robinson 2013). Advancing human and economic development requires active and effective governance capable of making relevant policy addressing present day challenges and providing quality welfare and services (Hughes et al. 2014). This is also the focus of Sustainable Development Goal (SDG) 16 (Peace, Justice and Strong Institutions), which aims at promoting the rule of law; substantially reducing corruption, developing effective, accountable and transparent institutions and building of institutional capacity at all levels (UN General Assembly 2015). Likewise, strengthening institutions to achieve beneficial social outcomes is central to the fulfilment of other SDGs, such as ending poverty in all its forms everywhere (SDG 1), achieving gender equality (SDG 5) and reducing inequality within and among countries (SDG 10) (UN General Assembly 2015).

With respect to countries' capacity to adapt to climate change, good governance and institutions have been identified as key conditions for the successful deployment of adaptation options (Eisenack et al. 2014; Klein et al. 2014). The IPCC's Fifth Assessment Report (AR5) characterizes adaptation barriers (or constraints) as "factors that make it harder to plan and implement adaptation actions or that restrict options". Lack of institutional capacity is identified as the most pertinent constraint to adaptation across many sectors (e.g. water, urban areas, human health, human security) and in all world regions (Klein et al. 2014). The numerous interventions that may enable or hinder adaptation – such as prioritizing policies, mobilizing resources, coordination of efforts, decision-making – are processes often contingent on the efficacy of institutional mechanisms (Klein et al. 2014). A recent review of economic literature on adoption of environmental policy, for instance, finds a positive relationship between policy adoption and various indicators of institutional quality (Dasgupta and De Cian 2018). Inept governance can even hinder a country's ability to realize adaptation goals and targets set according to the country's level of vulnerability (Berrang-Ford, Biesbroek, et al. 2019). Countries with better governance are also found to be more likely to receive adaptation aid from donors since it is assumed that adaptation funding will be used more effectively (Weiler et al. 2018).

In particular, the level of corruption within institutions, which is one of the main determinants of the quality of governance, is highly relevant for climate change adaptation (Lesnikowski, Ford, Berrang-Ford, Barrera, Heymann, et al. 2015; Berrang-Ford, Ford, et al. 2014). In a country with weak governance, investments in adaptation measures can potentially pose corruption risks (Mahmud and Prowse 2012). There is evidence that the level of corruption such as bribery and misuse of resources can be more severe in post-disaster operations as compared to the pre-disaster (Mahmud and Prowse 2012). Corruption weakens institutions, damages public trust and the strength of social contract, diverts funds from budgets and investments, interferes with the flow of development aid and hinders human capital formation (Mauro 1995; Abed et al. 2002). Improving governance and strengthening anti-corruption measures thus is critical for implementation of adaptation actions.

Understanding current and future evolution of governance is necessary for assessments of adaptive capacity and thereby the impacts of future climate change. Insights into the temporal evolution of adaptive capacity can also indicate the existence of limits to adaptation at a given point in time. Quantification of adaptive capacity also has practical application in climate impact models. Understanding governance outlook hence can reveal future challenges in climate change adaptation.

	SSP1	SSP2	SSP3	SSP4	SSP5
Governance	Effective	Modestly effective	Ineffective	Unequal within countries	Increasingly effective
Income	High	Medium	Very unequal between countries	Very unequal between and within countries	High
Higher education	High	Medium	Low	Unequal	High
Gender equality in education	High	Medium	Low	Unequal within countries	High

Table 2.1: Overview of representation of governance and its correlates in the five SSP scenarios

2.2 Governance in the Shared Socioeconomic Pathways

To operationalize and facilitate future climate impact assessments, the Shared-Socioeconomic Pathways (SSP) scenarios have been developed. The pathways are categorized along the assessed challenges to climate mitigation and adaptation. The five qualitative storylines describe different characteristics of and interactions between natural resources, economy, demography, lifestyle, human development, technology and institutions (O'Neill, Kriegler, et al. 2017). The SSPs provide a framework to assess a wide range of possible futures and societal changes both between and within countries, and the extent to which these conditions create challenges to mitigation and adaptation to climate change. Some adaptation-relevant dimensions including population and education (KC and Lutz 2017), urbanization (Jiang and O'Neill 2017) and income (Crespo Cuaresma 2017; Dellink et al. 2017; Leimbach et al. 2017), human development (Crespo Cuaresma and Lutz 2015) and inequality (Rao et al. 2018) have already been quantified in the SSP framework. A quantification of the SSPs in terms of future governance trajectories, however, has not yet been realized.

The departure point for the quantification of an indicator of governance along the five SSPs is the qualitative description in the scenarios' narratives (O'Neill, Kriegler, et al. 2017), captured by the characterization of institutions and their effectiveness as outlined in Table 2.1. SSP1 is the "green road" scenario, which envisages a rapid shift to sustainable development, increases in education and health investments, declining inequality both within and between countries, and de-emphasis on economic growth and reduction of resource intensity in favor of improving environmental conditions. Institutions are expected to become increasingly effective and international cooperation becomes persistent. Such features make the SSP1 world characterized by low challenges to both climate mitigation and adaptation as a result of inclusive economic growth and sustainable welfare. The “middle of the road“ scenario SSP2 is characterized by uneven and sluggish economic growth and development with slower progress towards achieving the SDGs. SSP2 does not differ substantially from the present-day trends. SSP2 is largely consistent with historical dynamics, but it takes into account dynamic relationships among socioeconomic determinants and convergence between countries. Institutions in SSP2 are modestly effective and uneven. SSP3, also termed the “rocky road” scenario, expects regional and global conflicts to result from international fragmentation and inter-country rivalry. Countries are preoccupied with national goals, which weakens international cooperation. Governance in SSP3 is rather ineffective and support for international and development institutions is reduced. “A road divided” or SSP4 presents low challenges to mitigation thanks to global technological advancement but high challenges to adaptation due to the unequal distribution of resources both within and across countries. Governance is assumed to be stronger in high-income regions whilst in low-income regions, basic human development is neglected and policy implementation is likely to be unsuccessful due to weak governance. Higher inequalities result in weak representation of the vulnerable groups and persistence of low levels of development. The SSP3 and SSP4 scenarios present the highest challenges to adaptation, caused by the combination of slow development, low education, high inequality and weak institutions. Finally, SSP5 is characterized by development driven by fossil fuel-intensive economies which enable countries to become richer and more equitable at the price of substantial environmental degradation. Similar to SSP1, the SSP5 scenario also assumes improved institutions and rapid human development, particularly for the currently disadvantaged populations. However, unlike in SSP1, the nature of the underlying growth in SSP5 relies heavily on fossil fuel use and results in high challenges to climate change mitigation (O'Neill, Kriegler, et al. 2017).

2.3 Future pathways of governance

In order to quantify and project governance trajectories along the SSPs scenarios, we rely on theoretical insights on the determinants of good governance for an empirical specification. Subsequently, an econometric model is employed to establish a relationship between governance and countries' socio-economic indicators of which projections along the five SSP scenarios are already available. Future projections of governance evolution within the SSP framework are then derived and can be used to evaluate the challenges to adaptation together with an internally consistent set of socioeconomic variables in the SSPs.

Given its breath and depth, governance (a dependent variable in our econometric model) and its dimensions can be conceptualized in many ways. Here we use the well-established Worldwide Governance Indicators (WGI) that provide a composite index for governance with six sub-categories: voice and accountability, political stability, government effectiveness, regulatory quality, rule of law and control of corruption. The indicators presented in this database aggregate perceptions of governance of a large number of enterprise, citizen and expert survey respondents from 31 different data sources provided by 25 different organizations, and provide a broad country coverage (Kaufmann 2010). The strength of the WGIs in capturing an inherently complex concept lays in its many different data sources that summarize information on the various dimensions of governance, and through averaging the data on the country level control for the possible idiosyncrasies between sources (Kaufmann et al. 2007).

The choice of the determinants of good governance (our explanatory variables) is based on modernization theory which posits that economic and educational development are central determinants of improvements in the rule of law (Inglehart and Welzel 2009; Epstein et al. 2006). There is, in addition, ample empirical evidence of a causal relationship between female representation in government and reduced levels of corruption (Jha and Sarangi 2018), as well as a strong connection between gender empowerment and democracy (Hughes et al. 2014). Within the SSP framework, economic as well as education trajectories are readily available (Crespo Cuaresma 2017; KC and Lutz 2017). For gender equality, we use the difference in mean years of schooling between men and women a proxy variable. This measure of gender equality arguably represents only one dimension of it, but gender gaps in education can be credibly taken as indicative of more widespread gender inequality issues in a society.

The model (see Methods) is estimated using a panel data for 173 countries for the time period from 1995 to 2015. Although governance indicators at the sub-national level are available for a few countries, the most granular SSP projections with global coverage for other socioeconomic variables are only available at the country level, which also defines our unit of cross-sectional variation.

2.4 Methods

2.4.1 Data

We use the Worldwide Governance Indicators (WGI) database, that provides a composite governance index based six categories: voice and accountability, political stability, government effectiveness, regulatory quality, rule of law and control of corruption. After standardizing the indicator from its original -2.5 to 2.5 range to the range from 0 to 1, our main response variable was the arithmetic average of the six components, referred to as the governance indicator throughout the paper. Historical GDP per capita is taken from the Penn World Table 7.0 (Heston et al. 2011) and SSP projections from Crespo Cuaresma (2017). Measures of education (share of population with post-secondary education) and gender equality in education (difference in mean years of schooling between men and women) come from the

Wittgenstein Centre for Demography and Global Human Capital (Wittgenstein Centre for Demography and Global Human Capital 2021).

2.4.2 Model

The estimation of the effects of the covariates mentioned above on the governance indicator was carried out using a yearly country-level panel data spanning the period between 1995 and 2015. Our main specification is as follows:

$$governance_{i,t} = \beta_1 lnGDP_{pc_{i,t}} + \beta_2 education_{i,t} + \beta_3 genderdifference_{i,t} + \alpha_i + \gamma_t + \varepsilon_{i,t}$$

where α_i controls for time-invariant country-specific characteristics, and γ_t accounts for common shocks in the sample in the form of year-fixed effects. Including fixed effects allows for the presence of omitted factors and long term trends that might affect both sides of the equation, therefore eliminating bias that might arise from cross-sectional analyses. We provide additional specifications in Annex A (Table A.1), and show that our results are robust for within and between-country regressions underscoring the robustness of our findings also in the light of cross-national differences.

We project the data forward to the year 2100 by using the coefficient estimates of the model given by equation (1) and imposing them over the internally consistent projections of GDP, education and gender gap in education which is given by the set of existing SSP projections. To remain consistent with the narratives, we account for the unobserved characteristics captured by the country fixed effects, which go beyond what can be explained with changes in governance and are likely to capture further intangible characteristics such as culture, by assuming that they will change over the long course of the projection period. In other words, we calculate rates of convergence between countries in line with the narratives which assume different degrees of reduction of inequality in various socio-economic characteristics: in SSP 1, all countries converge in 2130 to the 75th percentile of the present-day distribution, for SSP2 in 2250, SSP3 assumes no convergence at all, for SSP4 in 2250, and SSP5 in 2180.

2.4.3 Compositional analysis

The composite nature of our dependent variable (voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, control of corruption) allows for the investigation of whether some of the dimensions stand out in their relationship with the covariates. We treated our governance variable with an isometric-log transformation (van den Boogaart and Tolosana-Delgado 2013), and subsequently regressed it against our covariates. This process yields weights within each covariate that relate to each of the dimensions of the governance index, thereby disentangling the extent to which each of the covariates relates to the components of the governance indicator.

In our analysis of the composite Worldwide Governance Index (comprising six dimension of governance), we find a distinct relationship between post-secondary education and two dimensions of the dependent variable: control of corruption and government effectiveness (see Figure A.1 in Appendix A). This effect is not surprising and presents additional evidence concerning the importance of education (post-secondary education) for better institutions and demand for eradication of corruption (Lutz, Cuaresma, et al. 2010). Based on this finding, we separately project indicators of corruption and government effectiveness, thereby capturing the effect of different rate of change of educational expansion across the scenarios (see Figures A.2-A.5 in Appendix A).

Our econometric analysis shows that the aggregate governance indicator from the WGI database (Kaufmann 2010) can be well predicted using GDP per capita, the share of population with higher education and the gender gap in mean years of schooling (see Table A.1 in Appendix A). The estimated elasticities linking the variables in the specification to changes in governance indicators appear robust to changes in the modelling strategy. The estimates obtained from the model are then combined with the available country-level indicators of socio-economic

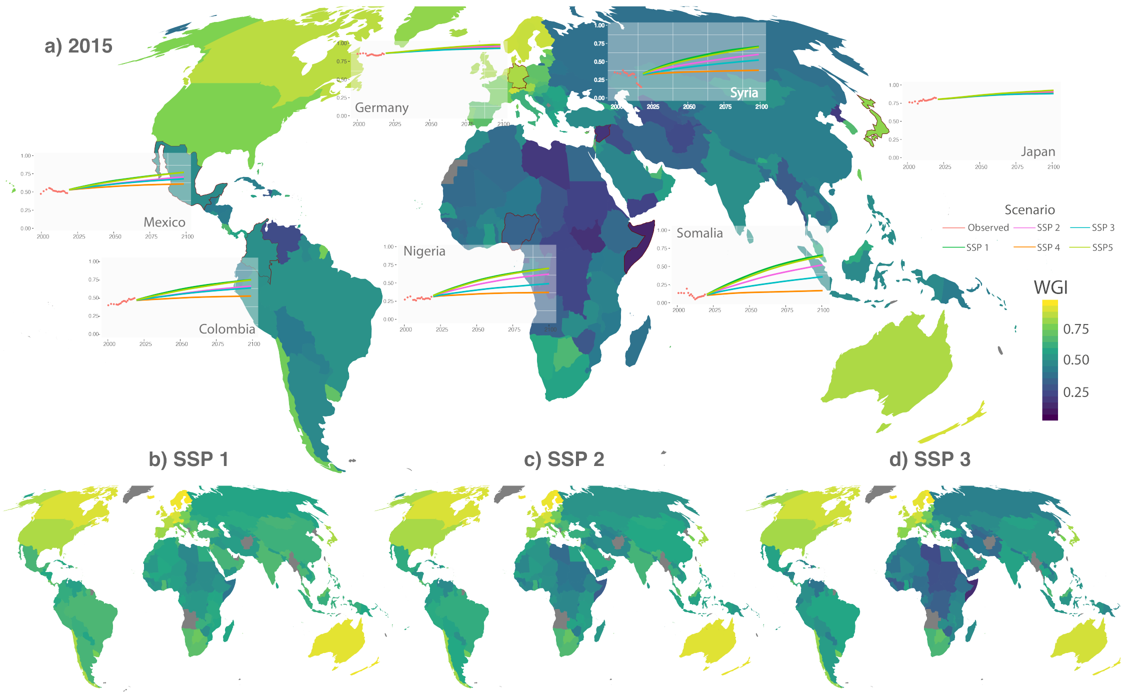

Figure 2.1: Evolution of governance over the 21st century. The 2015 values of the normalized composite world governance indicator (WGI) in 2015 are shown in a), overlaid with the scenario dependent evolution of governance for selected countries over the 21st century. The governance indicator is normalized to a range from 0 to 1, with higher values indicating better governance. The global distribution of future governance in 2050 is depicted for different SSPs ranging from a 'sustainable future' (SSP1, b) to a 'middle of the road' scenario (SSP2, c) and a 'rocky road' scenario characterized by unequal development and regional rivalry (SSP3, d).

performance within the SSP framework to calculate projections of the governance indicators over the 21st century.

In line with the SSP narratives, future projections of governance show distinct differences between the scenarios (Figure 2.1). For developed countries such as Germany or Japan, whether the country follows the most or the least progressive scenario makes only a minor difference for the dynamics of the projected governance indicator since their score remains very high in all scenarios. For less well-off countries, however, the path of the socio-economic development is decisive for how governance is expected to evolve (Figure 2.1 b,c,d): for countries like Somalia or Nigeria, the difference between following the SSP1 ("green road") and SSP3 ("rocky road") could result in anything from stagnation to trifold improvement.

Under the SSP3 scenario, little improvement in governance is projected globally over the 21st century. In contrast, substantial progress already by mid-century is evident under the SSP1 scenario which envisages a sustainable future. Similarities between SSP1 and SSP5 arise as a result of the almost identical representation of governance in the original storylines, which is reproduced in our projections. Although the development narrative and resulting climate mitigation challenges in SSP1 and SSP5 differ fundamentally, their socio-economic development trajectories are remarkably similar. SSP4 on the other hand, yields results that are in between SSP2 and SSP3. Because of these similarities, in two of the figures we report results for only for SSP1, SSP2 and SSP3.

There is no rule of thumb for which levels of this indicator represent 'good' governance. In fact, any such categorization arguably also includes value judgement. For the sake of illustrating the changes over the 21st century, however, we introduce percentile categories based on the 2015 distribution of the governance scores (see Figure 2.2). A clear scenario dependence for projected governance is apparent at a country level (Figure 2.2 a-c). The differences are even more striking when we consider the implications for future populations in countries with different governance regimes (Figure 2.2 d-f). Many countries whose populations are projected to grow substantially are expected to undergo transition and improve their governance over the coming decades, i.e. from "weak" to "medium", or further. Under the rapid development scenarios such as SSP1 and SSP5, this implies that only a small number of countries will be characterized by very weak or weak governance (defined as the state of a country below the median of the governance indicator today) and almost all countries may reach states of good governance by the end of the century. In contrast, countries that are home to around 3 (5) billion people in 2050 (2100), will continue to be characterized by weak governance under the SSP3 scenario (Figure 2.2). Even under a middle-of-the-road SSP2 scenario, about 1.5 billion people will be living in about 40 countries characterized by weak governance by mid-century.

The projection exercise combines short to medium-term dynamic adjustments based on the estimated relationships (and thus extrapolated using the correlation structures found in historical data) with assumption-driven long term developments

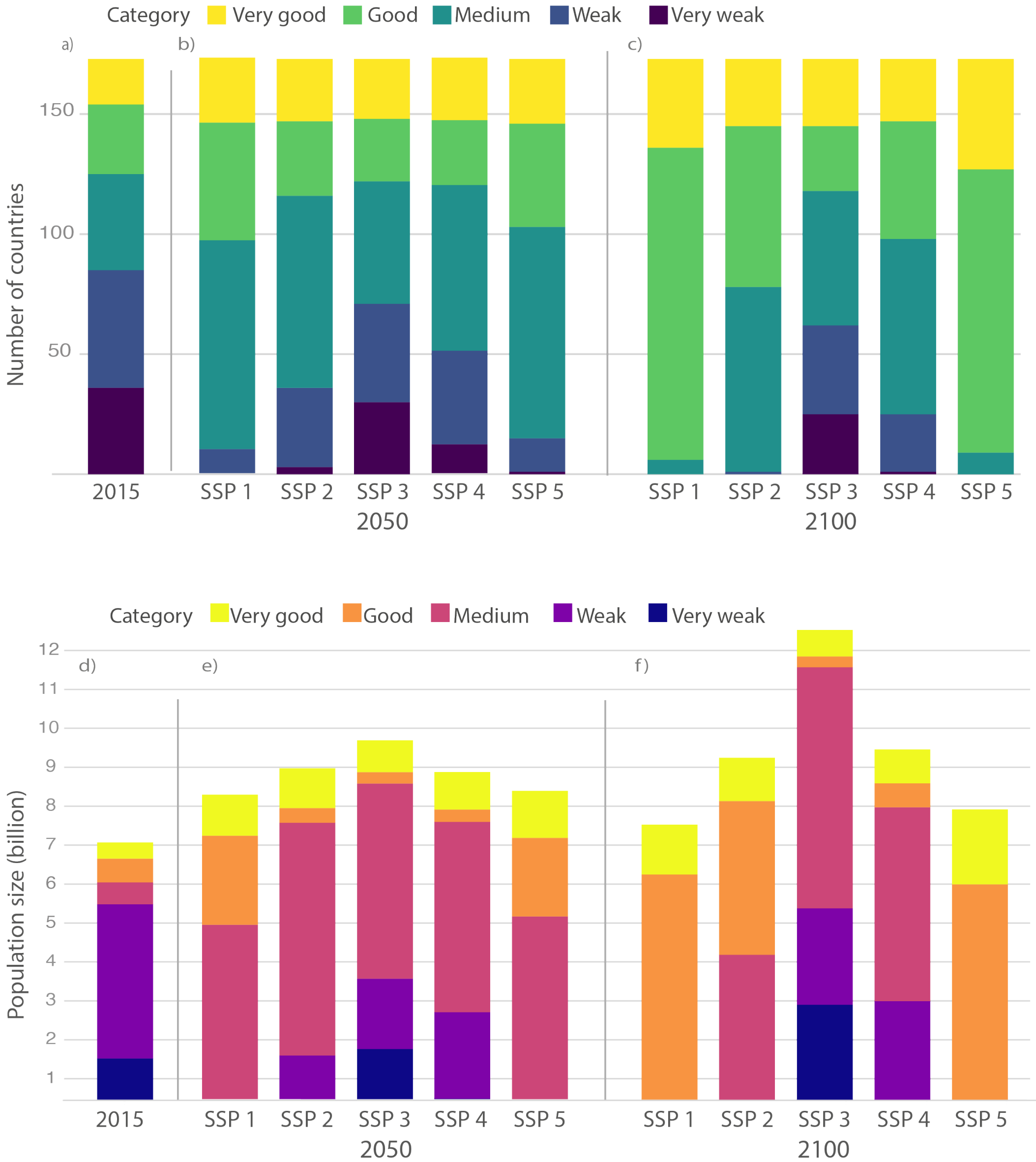

Figure 2.2: Projections of governance in countries grouped by income and population-specific projections. a-c, The number of countries per SSP in different governance categories for 2015, 2050 and 2100, respectively. The governance indicator is normalized with 0 indicating very low levels of governance across all indicators and 1 indicating very high levels (Kaufmann 2010). For illustration purposes, we introduce the following percentile-based categorization based on the 2015 governance scores : very good (>90th percentile), good (75 - 90), medium (50 - 74), weak (25 - 49), very weak (<25th percentile).d-f, Estimated population living in countries with different governance levels for 2015, 2050 and 2100. Total population size differ as a result of the diverging projections of future population under different SSPs.

that ensure the internal consistency of the trajectories with respect to the SSP narratives. Throughout the paper we report results solely for the aggregate governance indicator. However, the projections of the individual dimensions of the indicator can also be used if found to be particularly relevant for the socio-economic issue or a policy objective in focus. Based on our compositional analysis of the governance indicator, adjusted estimates of the effects of socioeconomic developments on particular components of the governance indicator are calculated to provide projections of specific subcomponents such as corruption or governance effectiveness (see Methods and Supplementary Information). This makes our results applicable to a wide range of issues under consideration in policy agendas related to sustainable development and climate actions.

It is important to highlight that our approach does not imply a direction of causal linkages. Improvements in governance in the context of sustainable development can lead to a virtuous cycle between governance and development, rather than showing a cause-and-effect relationship (Kraay and Kaufmann 2002). Since the focus of our model is not to unveil the causal effects, but rather to consistently extend the SSPs, such potential mutually re-enforcing dynamics only further underscore the need for an integration of governance into the SSP framework.

2.5 Importance of near-term improvements in governance

In a world with near-term sustainable development targets and ongoing climate change, the temporal evolution of our governance indicators is of particular interest. We find that countries characterized by very weak governance, albeit starting from a low level, have an up to five times higher rate of improvement in scenarios of rapid socio-economic development under SSP1 and SSP5 compared to SSP3 (Figure 2.3). The absolute values for countries in the 'medium' category is considerably smaller, although differences between the scenarios are still evident (up to a factor of four between SSP1 and SSP3). Over time, countries move out of the lower

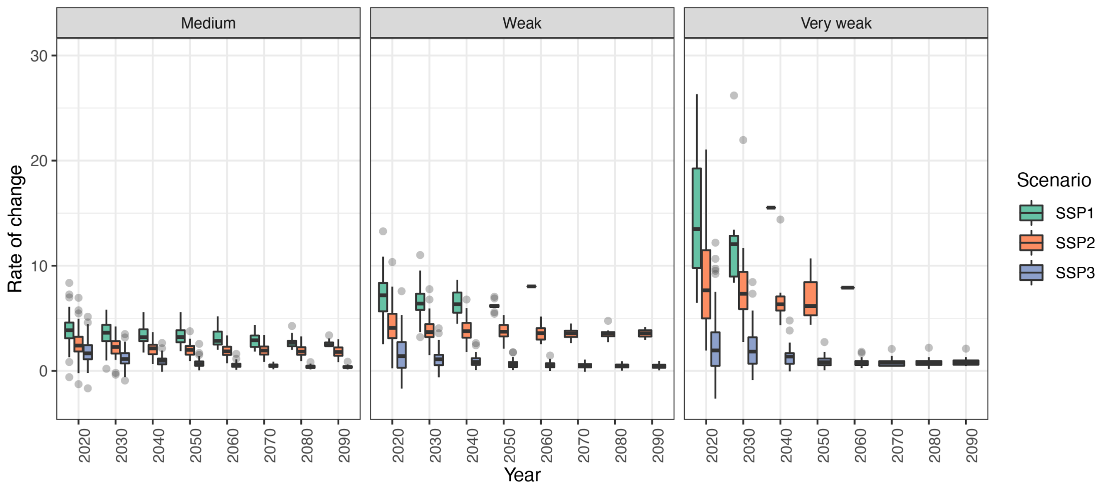

Figure 2.3: Rates of change of governance. Box-Whisker diagram of the five-year rates of change in governance for different SSPs over the 21st century. The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the highest value that is within 1.5 x interquartile range of the hinge. Data beyond the end of the whiskers are outliers and plotted as points. Panels separate out the evolution for country groupings classified by their state of governance (time-dependent). For SSP 1, no countries will be in the 'very weak' category after 2030 (2050) following high rates of improvement in governance in the preceding decades. SSP 4 and 5 are omitted from the figure for clarity.

categories, and their rates of change reduce as they improve governance. Our analysis suggests a window of opportunity to eradicate lowest levels of governance in the near term. This highlights the importance of achieving the goals under the 2030 Agenda for Sustainable Development to facilitate long-term sustainable development, particularly for the countries characterized by the lowest levels of development to date.

2.6 Governance and adaptation to climate change

Adaptation is multi-faceted and sector-dependent. As both the integral part of sustainable development and a stand-alone mechanism in coping with climate change, adaptive capacity is difficult to measure because of the volatile nature of its many determinants. Successful adaptation will depend in part on the timescales of improvement of socio-economic factors many of which are now available in the SSP framework. The existing projections including that of governance can subsequently

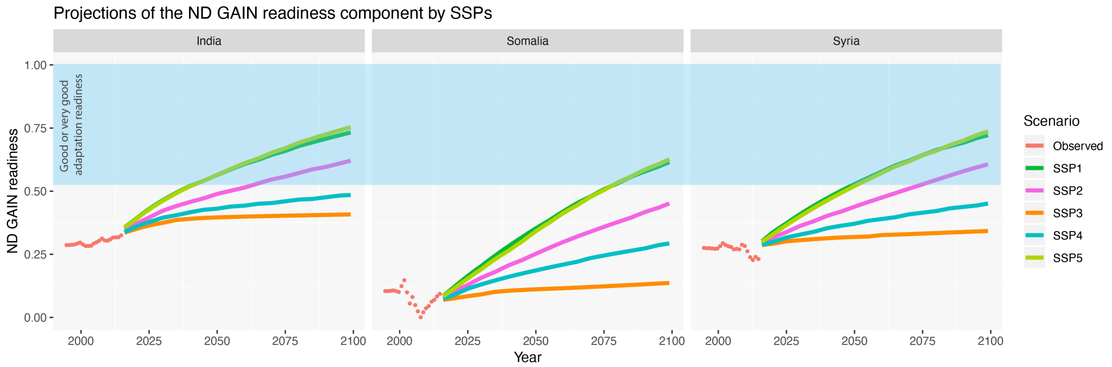

Figure 2.4: Projections of the ND GAIN Adaptation Readiness score. Trajectories for India, Somalia and Syria are shown for different SSPs. The projections of the Adaptation Readiness score are based on our projections of future governance. The shaded region marks the range of the readiness indicator for categories 'good' and 'very good' in 2015 (0.52-0.80). For global projections see in Annex 1, Figures 6 and 7.

be used for designing an overarching framework to evaluate more granular and sector-specific measurements of adaptive capacity.

Across all scales, however, a key determinant is the ability to effectively leverage private and public sector investment for adaptation actions. This is coined "adaptation readiness" in the Notre Dame Global Adaptation Index (ND-GAIN) (Chen et al. 2015), a summary indicator of countries' vulnerability to climate change. The concept of adaptation readiness can also be seen as an indication for countries' absorptive capacities of international climate finance channeled, for instance, through the Green Climate Fund (Brechin and Espinoza 2017). If the readiness is low, successful adaptation financing and implementation is questionable. Governance is indeed a key ingredient in the ND-GAIN readiness score. Given the high correlation of the readiness score with our governance indicator (0.93, p = 0.000), our projections thereby allow us to deduce the future trajectories of the ND-GAIN readiness score in line with the different SSP scenarios.

The range of adaptation readiness spanned by the member states of the Organization for Economic Cooperation and Development (OECD) today match well with our 'good' and 'very good' categories. Most developing countries, however, will barely, if at all, reach levels of 'good' adaptation readiness by mid-century, even under the optimistic scenarios SSP1 and SSP5 (Figure 2.4). Under SSP3 and SSP4, little to no improvement in adaptation readiness is apparent, with an ever increasing number of people living in countries with low adaptive capacity (see Figures A.6 and A.7 in Annex A). Our results are fully in line with the qualitative classification of adaptation challenges in the SSP scenarios: low challenges in SSP1 and SSP5; and high challenges in SSP 3 and SSP4 (O'Neill, Kriegler, et al. 2017). However, we also show that 'low challenges' are not equivalent to 'no challenges'. Even under SSP 1, adaptive capacity will only increase gradually over the next decades while an adaptation deficit to present day climate is already apparent (Lobell and Tebaldi 2014). To that end, our results also illustrate what could be considered an 'upper limit' of the future evolution of adaptive capacity.

2.7 Timescales of governance and climate change

The recent IPCC Special Report on Global Warming of 1.5°C (IPCC 2018) has underscored the substantial differences in climate impacts between 1.5°C and 2°C that could materialize already before mid-century. Tropical regions will be bearing the brunt of these differences (Schleussner, Lissner, et al. 2016; Schleussner, Deryng, et al. 2018; King and Harrington 2018) and will also be the regions where the anthropogenic climate change is emerging the fastest against the background of natural variability (King, Black, et al. 2016). Thereby, while vulnerable countries will be striving for sustainable development and improving their adaptive capacity, climate impacts will continue to intensify. Our results show that even under scenarios of rapid and sustainable development (SSP1 and SSP5), improvements of adaptive capacity will take on average at least three decades. This indicates that (temporal) limits to improvements in adaptive capacity may persist during the 21st century leading to elevated risks and impacts of climate change in countries with low socio-economic development. Climate impacts that exceed the limits to adaptation will result in climate-related loss and damage (Mace and Verheyen 2016; Serdeczny et al. 2017; James et al. 2015). Given that negative climate impacts can hamper countries' abilities to achieve sustainable development, and thereby improving adaptive capacity, our results indicate that adequate responses and support schemes for loss and damage will be crucial policy instruments to support vulnerable countries (Thomas and Benjamin 2017).

Country-level representation of governance does have several limitations. The methodological framework used for the projection exercise presented in this study can be complemented with methods to downscale global assumptions and estimates. Scenario narratives and local interpretations of the SSPs can be derived from qualitative methods. The analytical methods employed to provide inference on the drivers of institutional change rely on the assumption of a common response of the governance indicators to their determinants across countries. Combining the advantages of a global analytical model of governance dynamics such as the one presented here with those of a narrative based on a qualitative context-specific assessment of future governance changes can improve the quality of our projections further. Such an extension of our analysis appears particularly important for countries for which the existing data are missing or not reliable, as well as for countries where disruptive changes in the current institutional setting are likely in the future. To address the issue of internal inequalities and sub-national specificities, we here have to rely on our indicator's multiple sources and dimensions. An analysis incorporating sub-national information is a promising research avenue. Further unobserved differences between countries are controlled for in our model by using country-specific fixed effects, and global trends by yearly fixed effects.

The SSP narrative framework by design does not incorporate feedbacks of climate impacts. This is important to keep in mind, particularly in the context of high warming scenarios or in scenarios with persistently low levels of development in some regions of the world. Even under the SSP3 scenario, no country is projected to see a decline in socio-economic development. This 'scenario optimism' can stand in stark contrast to the observed dynamics, where in reality some countries such as Syria have experienced rapid decline in stability over the past recent years (Figure 2.1 a). The dynamics behind such deteriorations are difficult to incorporate in deterministic modelling approaches underlying the SSPs, which represents a limitation of scenario frameworks in general. While conflicts are context-dependent and not deterministic, some key determinants of conflict risks can be linked to the SSP pathways and indicate increasing globally increasing conflict risks for SSP3 and SSP4 centered in Central and South Asia as well as Africa (Hegre et al. 2016). Considering such risks would lead to considerably higher probabilities for a deterioration of governance under those scenarios, thereby painting a more accurate, but even bleaker picture compared to the sustainable development scenarios.

Uncertainties related to trajectories of future vulnerability have been found to dominate climate impacts in the near term (Hallegatte et al. 2015), but will also shape the end-of-century climate impacts (Hinkel, Vuuren, et al. 2012). Climate-related natural disasters displace millions (Heslin et al. 2019) already today, cause multi-billion dollar damages (Munich Re 2018) and may even contribute to increased risks of armed conflict outbreaks (Schleussner, Lissner, et al. 2016) and exacerbate forced migration (Abel et al. 2019). Projections of future economic impacts of climate change indicate non-linear increases in damages, which are most pronounced for tropical countries (Burke, Hsiang, et al. 2015). Thereby, integrating climate change impacts into SSP trajectories would affect the global trajectories of socio-economic development, in particular for high emission scenarios. To do so, however, requires an improved understanding of the prospects of future adaptation. The projections of governance and adaptive capacity provided here contribute to closing this gap. Our study thus presents a step forward towards a more integrated scenario perspective to inform global policies aimed at achieving sustainable development.

Acknowledgements

The authors express their gratitude to the scientific community for developing the SSP scenarios and to the International Institute for Advanced System Analysis (IIASA) for hosting the SSP database. MA and CFS acknowledge support by the German Federal Ministry of Education and Research (01LN1711A).

Code availability

Code underlying the results is available at `https://github.com/marina-andrijevic/governance2019` Data availability: Governance data is available on the Worldwide Governance Indicators website (`https://info.worldbank.org/governance/wgi/#home`) . Historical GDP was obtained from the Penn World Tables 7.0 (`https://www.rug.nl/ggdc/productivity/pwt/pwt-releases/pwt-7.0`) and projected values through the IIASA SSP database (`https://tntcat.iiasa.ac.at/SspDb/`). Data on educational attainment and gender equality in education is accessible through the Data Explorer of the Wittgenstein Centre for Demography and Global Human Capita.

3

Overcoming gender inequality for climate resilient development

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Abstract

Gender inequalities are reflected in differential vulnerability and exposure to the hazards posed by climate change and addressing them is key to increase the adaptive capacities of societies. We provide trajectories of the Gender Inequality Index (GII) alongside the Shared-Socioeconomic Pathways (SSPs), a scenario framework widely used in climate science. Here we find that rapid improvements in gender inequality are possible under a sustainable development scenario already in the near-term. The share of girls growing up in countries with the highest gender inequality could be reduced to 24% in 2030 compared to about 70% today. Largely overcoming gender inequality as assessed in the GII would be within reach by mid-century. Under less optimistic scenarios, gender inequality may persist throughout the 21st century. Our results highlight the importance of incorporating gender in scenarios assessing future climate impacts and underscore the relevance of addressing gender inequalities in policies aiming to foster climate resilient development.

3.1 Introduction

Differential risks to climate change impacts are shaped by variations in vulnerability and exposure within and across societies. Together with their biophysical determinants, vulnerability and exposure are products of unevenly distributed socioeconomic development and multidimensional inequality (Klein et al. 2014). Inequalities are reflected in income and wealth, which remain central subjects of socioeconomic research, but also in gender, education, racial and ethnic profiles (Mcdowell et al. 2016). Socially marginalized groups are often affected by the interplay of these different dimensions and are more vulnerable to the impacts of climate change.

A growing body of literature points at the facets of differential vulnerability and exposure to the impacts of climate change across genders, stressing that women are not inherently more at risk, but that intersections between gender, power dynamics, socio-economic structures and societal expectations result in climate impacts being experienced very differently by women (Djoudi et al. 2016). Research has also highlighted missed opportunities for action when women's agency in policy and decision making is not fully seized (Olsson et al. 2014). In our contribution, we focus on the role of gender inequality, which despite its prominence as a cross-cutting theme in the sustainable development discourse, lacks concrete operationalizations in the analysis of future impacts of climate change and the extent to which these can still be avoided (Pearse 2017).

Current and future damages of climate change are tied to the ability with which affected regions and populations adapt to changing conditions. In the risk framework of the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC), vulnerability to climate change impacts is inextricably linked to adaptive capacity, which is defined as "the ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC 2014). Adaptive capacity, in turn, hinges on a range of socioeconomic factors, gender inequality playing one of the central roles, particularly in areas most vulnerable to climate change. The linkages between gender inequality and adaptive capacity range from uneven access to resources, to cultural norms and entrenched social structures (Rao 2017; Alston 2013).

Accounting for gender inequality and its possible future trajectories in the assessment of the pathways of adaptive capacity adds another layer to the identification of societal climate impact hotspots – areas where expected biophysical impacts intersect with socioeconomic vulnerability (Schleussner, Lissner, et al. 2016; Byers et al. 2018). In this paper, we present an extension of the set of socioeconomic scenarios – the Shared Socioeconomic Pathways (SSPs) (O'Neill, Kriegler, et al. 2017) – with an indicator of gender inequality, the Gender Inequality Index (GII) (UNDP 2018) of the United Nations Development Programme (UNDP). The SSPs are a widely used toolkit in climate change research and provide a basis for the operationalization of indicators of gender inequality in integrated assessments.

The GII used here to reflect gender inequality consists of three dimensions: health (maternal mortality ratio and adolescent birth rates), educational and political empowerment (male to female ratio in parliamentary seats and secondary education) and participation in the labor market (male to female ratio in labor force participation rates, see the Methods section for additional details on the indicator) (UNDP 2018). We collected the individual components from their respective original sources and reconstructed the index following the approach laid out in the Technical Notes of the Human Development Report (UNDP 2018). This reconstruction produced more complete time series than those available hitherto (see Figure B.1 in Appendix B). The index ranges from 0 to 1, with higher values reflecting higher levels of inequality between men and women.

The multi-faceted nature of gender inequality at all levels of socio-economic development makes aggregation into indicator a complex exercise. Unsurprisingly, most indicators (including the GII), face justified criticism (Permanyer 2013; Beneria and Permanyer 2010) (see the Methods section for an extended discussion). We consider the dimensions covered in the GII to describe necessary conditions of gender inequality, while acknowledging that they are not sufficient to characterize

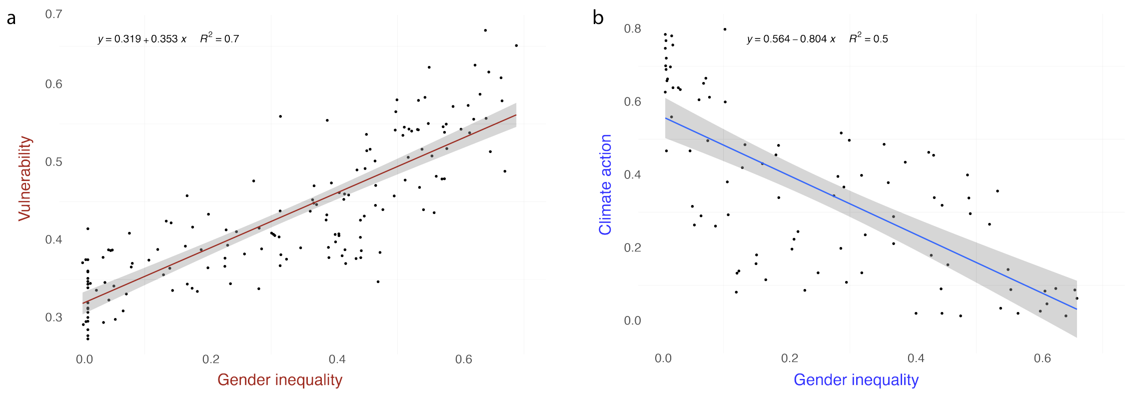

Figure 3.1: Gender Inequality Index (GII) - correlation with vulnerability and climate actions. a, GII vs. vulnerability component of the ND-GAIN index (country-level estimates for 2017). b, GII (country-level average 2005-2010) vs. CLIMI (country communications of climate policies between 2005 and 2010).

gender inequality across all the dimensions that contribute to it. In the light of these caveats, overcoming the inequality dimensions covered in the GII does not automatically mean that universal gender equality is achieved, and we do not assert that any country in the world can claim to have achieved full gender equality to date or in the near future. It is important to keep these limitations in mind when interpreting the results.

The ramifications of gender inequality for addressing climate change can be regarded through two lenses: women's differential vulnerability and adaptive capacity; and the role of women in mitigation and adaptation actions. To illustrate the importance of accounting for gender inequality in both adaptation and mitigation of climate change, we correlate the GII with an adaptation- and a mitigation-relevant metrics (compare Figure 3.1).

Previous research shows that the gender-differentiated vulnerability to climate change is most pronounced in agriculture (Caretta and Börjeson 2015; Su et al. 2017) and water (Sinharoy and Caruso 2019; Sultana 2018) sectors, natural disasters (Neumayer and Pluemper 2007), reproductive health (Sorensen et al. 2018), mental health and well-being (Castañeda Carney et al. 2020). We use a broad measure of climate change vulnerability of the Notre Dame Global Adaptation Index (ND-GAIN) (Chen et al. 2015), a widely used summary measure of a country's vulnerability to climate change and its readiness to improve resilience (for more applications, see (Adams et al. 2018; Robinson and Dornan 2017; Lesnikowski, Ford, Berrang-Ford, Barrera, and Heymann 2013). Figure 3.1a depicts the correlation between the GII and the ND-GAIN vulnerability indicator (consisting of six life-supporting sectors: food, water, health, ecosystem services, human habitat and infrastructure), and depicts a strong positive relationship between the two variables.

At the same time, a strand of research suggests that women's representation in politics leads to more stringent climate action (Mavisakalyan and Tarverdi 2019; McKinney and Fulkerson 2015), thus making a case for consideration of mainstreaming gender equality in mitigation. More broadly, female participation in decision-making is closely linked to various facets of socioeconomic progress: from higher spending on health and education to better quality of institutions, democracy and higher economic growth (Lutz, Cuaresma, et al. 2010; Mavisakalyan 2014; Clots-Figueras 2012; Mavisakalyan and Tarverdi 2019). Following a recent approach (Mavisakalyan and Tarverdi 2019), in Figure 3.1b we correlate the GII with the Climate Laws, Institutions and Measures Index (CLIMI) (Steves and Teytelboym 2013), an measure of climate change mitigation policies set by countries (for more applications, see Fredriksson and Neumayer (2013)). The correlation of the two indices suggests that low levels of gender inequality tend to occur in parallel to high levels of climate action, which corroborates previous research (Mavisakalyan and Tarverdi 2019).

Results and discussion While the importance of rapid and stringent mitigation cannot be overemphasized, and recent research insights provide indications that gender equality facilitates climate action, here we focus on the importance of gender equality for adaptive capacity and vulnerability to climate change. To this end, we expand the scenario space of the Shared Socioeconomic Pathways (SSPs), with the intention of improving the understanding of adaptation challenges under different socio-economic conditions. The SSPs are scenarios that explore a range of possible futures that illustrate how socio-economic conditions might change over the next century and what implications these conditions may have for climate change adaptation and mitigation. SSPs quantify five different narratives of socio-economic futures to operationalize them for climate change research (O'Neill, Kriegler, et al. 2017) – they are a widely used tool in climate research community, indispensable for integrated assessments of the dynamics between socioeconomic and climate change variables, and are also the scenario framework used in the Sixth Assessment report of the IPCC.

SSP1, the 'sustainability' scenario, is characterized by low challenges to mitigation and adaptation, a result of increased investments in education, health, renewable energy sources and declining inequalities between and within countries, thus limiting impacts and increasing adaptive capacity. SSP2, the 'middle of the road' scenario, maintains premediated challenges to adaptation and mitigation, and is a pathway of uneven and slower socioeconomic progress, compatible with the continuation of historical trends. SSP3 is characterized by high challenges to both mitigation and adaptation, which are a product of a growing divergence between economies, weak international cooperation and increase in internal and international conflicts. SSP4, the scenario of 'inequality', leads to low challenges for mitigation, due to technological advancements in high income countries, but high challenges for adaptation, because of an unequal distribution of advancements and resources across countries. Finally, SSP5 is similar to SSP1 in the fast socioeconomic progress on all fronts, but with the major difference of the progress being powered by fossil fuels, which produces substantially higher emissions and resulting climate impacts.

So far, the SSPs storylines have been quantified in future trajectories of income (Crespo Cuaresma 2017; Dellink et al. 2017), population (KC and Lutz 2017), education (KC and Lutz 2017), urbanization (Jiang and O'Neill 2017), the Human Development Index (Crespo Cuaresma and Lutz 2015), inequality (Rao et al. 2018) and governance (Andrijevic, Crespo Cuaresma, et al. 2020a). Gender inequality is qualitatively featured in the scenarios' storylines focusing on the demographic and human development elements (see Table 3.1 (O'Neill, Kriegler, et al. 2017)), and is to a certain extent reflected in the measures of discrepancies in educational attainment between men and women in the population projections by age and sex

	SSP1	SSP2	SSP3	SSP4	SSP5
Gender Inequality	Low	Medium	High	High in LICs, low in HICs	High

Table 3.1: Representation of gender inequality in SSP storylines. (HIC/LIC: High/Low Income Countries).

(KC and Lutz 2017). Our contribution provides projections of gender inequality, as quantified by the GII, which are compatible with the SSP scenarios described above and thus provide a new dimension to the assessment of potential future climate change adaptation pathways.

To achieve an internally consistent extension of the SSPs, we use the existing indicators under the SSP framework to analyze past trends and project future dynamics of gender equality. Our results indicate that past trends in the GII can be robustly explained by the dynamics of GDP per capita, population with post-secondary education and the gender gap in mean years of schooling after controlling for country-specific equilibria and global trends (see Methods for regression results and Supplementary Material for a sensitivity analysis). As is the case within the methodological framework of the SSPs, the projections of the GII are not to be interpreted as predictions, but as quantifications of narrative-driven scenarios.

3.2 Methods

3.2.1 Data

Gender Inequality Index (GII): the analysis in this paper is based on the GII, produced by the United Nations Development Programme (UNDP 2018). It integrates measures of reproductive health (maternal mortality ratio, adolescent birth rate), empowerment (secondary education, parliamentary seats) and labor market outputs (labor force participation rate).

The GII has been criticized on several grounds (Permanyer 2013; Klasen 2017), with key issues relating to its functional form (which is asserted to be unnecessarily complex and difficult to interpret); the health dimension of the index variables not having a male equivalent (unlike the dimensions of economic, political and labor market metrics); and the potential penalization of poor countries owing to the possibility that poor reproductive health is a result of general poverty rather than gender inequality. Attempts have been made to simplify the index and make its interpretation more intuitive, though no clear consensus on how exactly the adapted indicator should look like has been reached, and to our best knowledge, the UNDP has not made any amends to the index so far.

The criticism about the penalization of less developed countries is concerned with the indicator's health dimensions (i.e. maternal mortality and adolescent birth rates), which could be caused by poverty rather than gender inequality, thereby obscuring the implications of this dimension. The very rationale behind accounting for maternal mortality and adolescent birth rate as a dimension of gendered health inequality stems from the fact that poor maternal health sets women back uniquely, irrespective of the reason and without an equivalent risk for men, and as such arguably contributes to gender inequality. Reducing maternal mortality and adolescent pregnancy are also among the targets of the Sustainable Development Goal 5 on gender equality (UN General Assembly 2015). Additionally, recent applications found that the GII explains variance in child malnutrition and mortality in low and middle-income countries with similar income levels (Marphatia et al. 2016),implying that there the index does provide information on the variation of gender inequality across countries beyond that contained in GDP per capita differences. Finally, the fact that reproductive health is strongly affected by climate change impacts such as extreme heat is particularly relevant for the projection exercise presented here, and as such merits consideration as an own standing dimension of climate adaptation (Bekkar et al. 2020).

Further support for the GII's reflection of a broader understanding of gender inequality can be found in studies where it is found to correlate with other manifestations of gender inequality that go beyond what is included in the calculation of the index, such as the suicide gender ratio (Chang et al. 2019), adolescent dating violence (Gressard et al. 2015) and intimate partner violence (Redding et al. 2017).

3.2.2 Alternative indicators of gender equality

Alternative indicators available in the literature incorporate different aspects of gender inequality. In the following, three other indicators will be introduced and examined in relation to the GII.

Gender Development Index (GDI): The GDI (UNDP 2018) is designed within the Human Development Reports provided by the United Nations Development Programme. Similarly to the Gender Inequality Index, it accounts for metrics of health, education and economic empowerment. The economic component of the index is difficult to reconstruct due to the scarcity of data on the wage gap between women and men, which is necessary for the calculation of the overall index. Additionally, variation between countries is not as large as in the GII index, and the GDI does not capture basic metrics such as maternal and adolescent health, which are relevant for climate change vulnerability. The correlation of the GDI with the GII is depicted in Figure 5a.

Women, Peace and Security Index (WPS): The WPS is provided by the Georgetown Institute for Women, Peace and Security and index captures three dimensions: inclusion (economic, social, political), justice (formal laws and informal discrimination) and security (violence, safety). Even though this index incorporates dimensions of high relevance for climate change-related vulnerability (particularly violence), it is only available at two points in time and is therefore suboptimal for the estimation of the historical response function that underpins our analysis. However, it is highly correlated to the GII used in this paper (see Figure 3.2b).

Global Gender Gap Index (GGI): produced by the World Economic Forum, the GGI (World Economic Forum 2018) incorporates four dimensions: economic participation, educational attainment, health and survival and political empowerment. The dimensions are represented by 14 different indicators. Compared to the GII used in this analysis, the GGI contains similar dimensions and there are overlaps among the underlying indicators to the GII used in this analysis, while the major difference is in the health component, where the GII considers

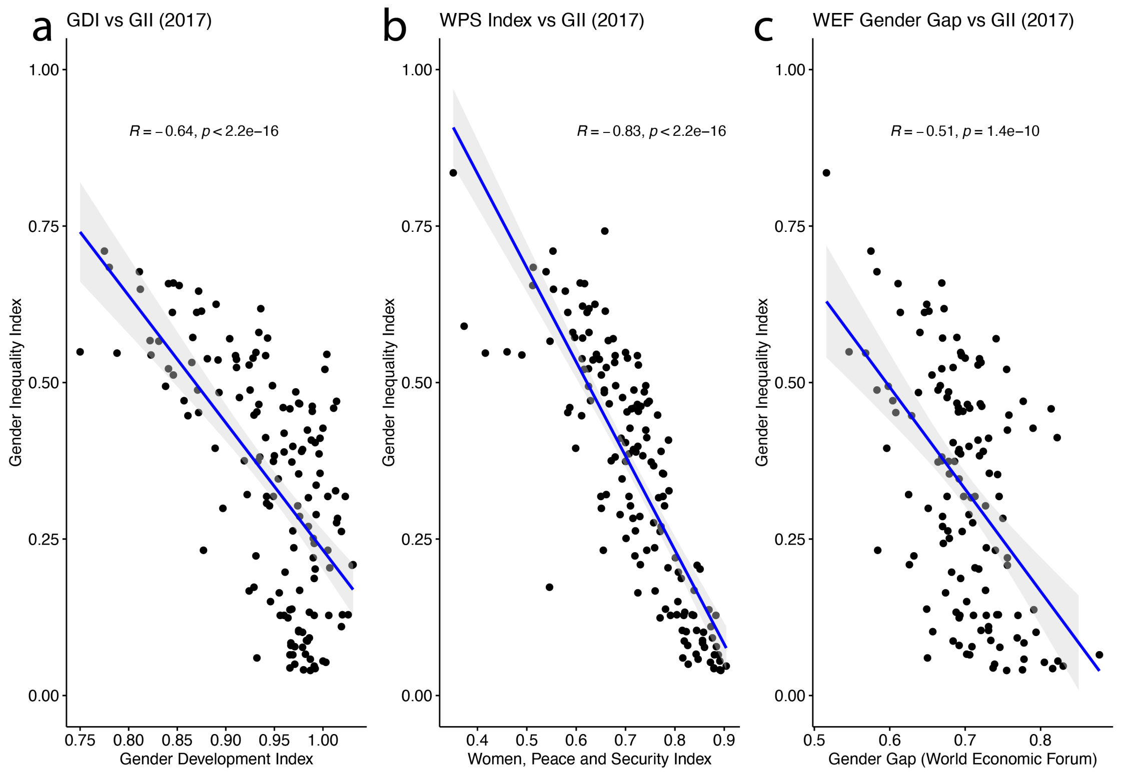

Figure 3.2: Comparison of the GII and other indices of gender equality. Correlation coefficient (R) and the statistical significance (p) are provided for the relationship between GII and a, Gender Development Index, b, Women, Peace and Security Index and c, Gender Gap index.

maternal mortality and adolescent pregnancy, while the GGG takes into account life expectancy. Similarly to other indices, the time series of GGG is shorter than that of the GII. The GGI has the lowest (albeit statistically significant) correlation coefficient with the GII (Figure 3.2c).

3.2.3 Gender equality indicators and climate adaptation

Compared to other commonly used indicators including the Gender Development Index (UNDP 2018), the Gender Empowerment Measure (World Economic Forum 2018), and the Women, Peace and Security Index, we find that the GII is particularly indicative of hindered adaptive capacity in many climate-vulnerable countries, since its dimensions (such as maternal health, participation in economic and political life) point at the very basic disempowerment of women that directly reduces their capacity to adapt to climate change. The GII is also more holistic in its economic dimension, by considering education and labor force participation rather than income, since the data on gender gap in earned income tends to be problematic (Bardhan and Klasen 1999). In addition, the construction of the GII precludes the different dimensions of the indicator from compensating for each other (i.e. poor performance in one dimension cannot be compensated for with higher performance in another dimension in GII). A more in-depth qualitative and quantitative comparison is provided below.While this is beyond the scope of this paper, application of our analytical framework to different indicators of gender inequality and analyzing the effect of the choice of the indicator on projections could be a fruitful research avenue.

Following the approach laid out in the Technical Notes of the Human Development Report (2018), we reconstructed the GII with the same underlying indicators, with the aim of obtaining more complete time series than those available hitherto. The data are available for majority of countries and can be reconstructed back to 1995 (see Figure B.1 in Appendix B). To capitalize on data availability and completeness, we use the same source indicators except for the education component, which we source from the Wittgenstein Centre for Demography and Global Human Capital (KC and Lutz 2017) for better consistency with the projections that follow in the second stage of the analysis. The calculation of inequality uses an association-sensitive method, with geometric means of the three dimensions calculated for each gender separately, and then aggregated across genders using a harmonic mean. For comparison of the reconstructed GII and the data provided through the UNDP website, see Figure B.1 in Appendix B. Data analysis and projections were done using R software version 1.3.1073.

3.2.4 Model

To analyze the relationship between gender inequality and other socio-economic dimensions, we use a simple econometric model that expresses the GII as a function of GDP per capita, the share of population with higher education and the difference in mean years of schooling between men and women, and accounts for country-specific time-invariant characteristics using fixed effects. The model is aimed at replicating long-run dynamics in GII, with the theoretical underpinning that trends in socioeconomic variables correlate with the changes observed in gender inequality over long periods of time. From an econometric point of view, it can be considered a cointegration relationship posing common trends in gender inequality, income and human capital indicators around a country-specific equilibrium.

Prior to the analysis, the GII is transformed to account for the bounded nature of the index, which is defined between 0 and 1. The variable used in the panel regression models is given by $GII^* = log(\frac{GII_{i,t}}{1-GII_{i,t}})$, where $GII_{i,t}$ is the original Gender Inequality Index for country i in period tt. Our basic specification is given by:

$$GII_{i,t} = \beta_1 \ln\left(GDP_{pc}\right)_{i,t} + \ \beta_2 \text{education}_{i,t} + \beta_3 \text{educationgap}_{i,t} + \alpha_i + \ \varepsilon_{i,t}$$

where α_i captures country fixed effects and $\varepsilon_{i,t}$ is the error term, assumed to be stationary. Several robustness checks carried out by changing the specification can be found in Table B.1 in Appendix B.

Projections for the 21st century are carried out by combining the parameter estimates from the specification given by equation (1) with the existing projections of GDP (Crespo Cuaresma 2017), population by age, sex and education (KC and Lutz 2017) and gender gap in education (KC and Lutz 2017) thereby remaining internally consistent with the SSP scenario framework and providing direct comparability with the rest of the socioeconomic projections existing. The SSP population projections (KC and Lutz 2017) were employed to derive the proportion of women experiencing different levels of gender inequality in the future at the global level. We split the population of women into two age groups: 0-14 and 15+. The thresholds for dividing the distribution of GII are based on the levels of gender inequality currently in the OECD countries (0.002 – 0.315).

3.3 Results

Our projection exercise shows that major improvements in terms of overcoming gender inequality are achieved worldwide by mid-century under the SSP 1 scenario

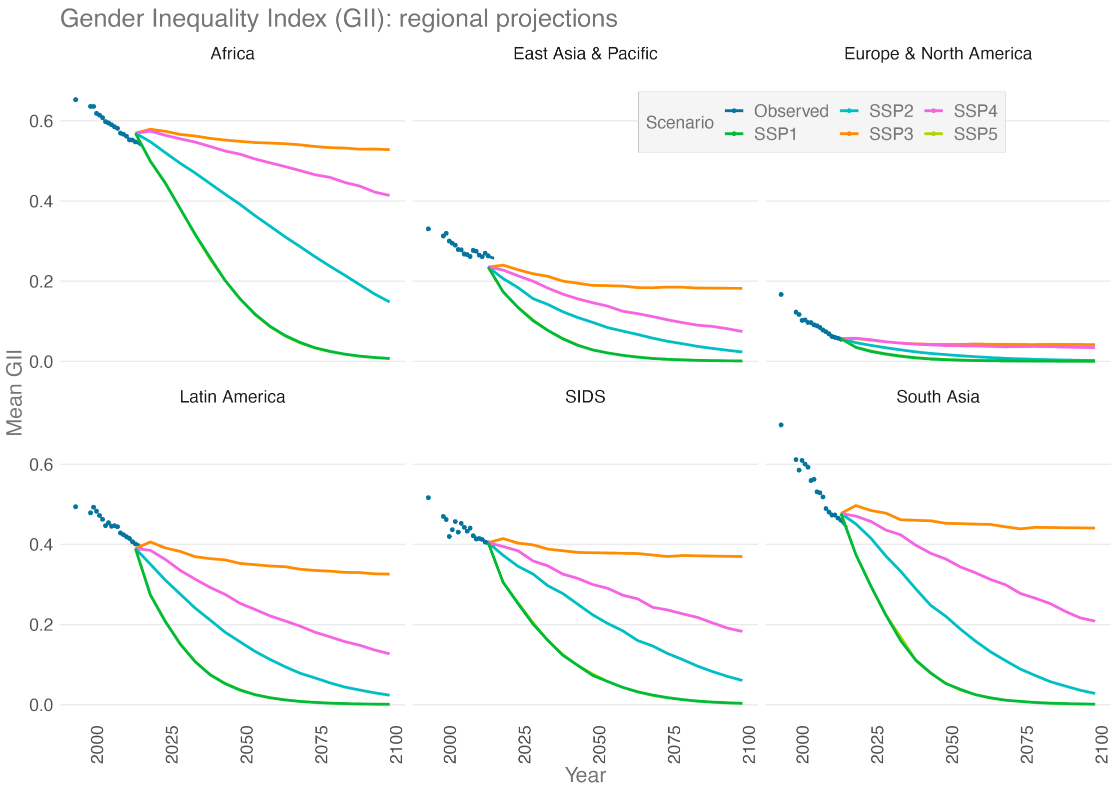

Figure 3.3: Evolution of the GII over the 21st century - regional outlook. Historical values of the GII index and projections over five SSP scenarios, averaged by world region.

(Figure 3.3c). Significant improvements happen following the SSP2 (Figure 3.3d) pathway, though with notable exceptions in the most vulnerable parts of the world. In the SSP3 world (Figure 3.3e), however, only marginal progress is made in parts of Latin America, while in Sub Saharan Africa gender inequality is projected to deteriorate (compare Figure 3.3e).

Given the central role that gender equality has for adaptive capacity, the future outlook concerning how well a country or a region can cope with the impacts of climate change can be very different depending on the scenario of socio-economic development. Across all world regions, improvements in gender equality in inclusive high-development pathways (SSP1, 5) are most pronounced in the near-term until mid-century. Note that the trajectories for SSPs 1 and 5 largely overlap due to similar levels of the underlying dimensions that gender inequality is a function of (education, GDP and gender gap in mean years of schooling). The summary of regional levels of gender inequality in Figure 3.3 reflects the severity of the difference

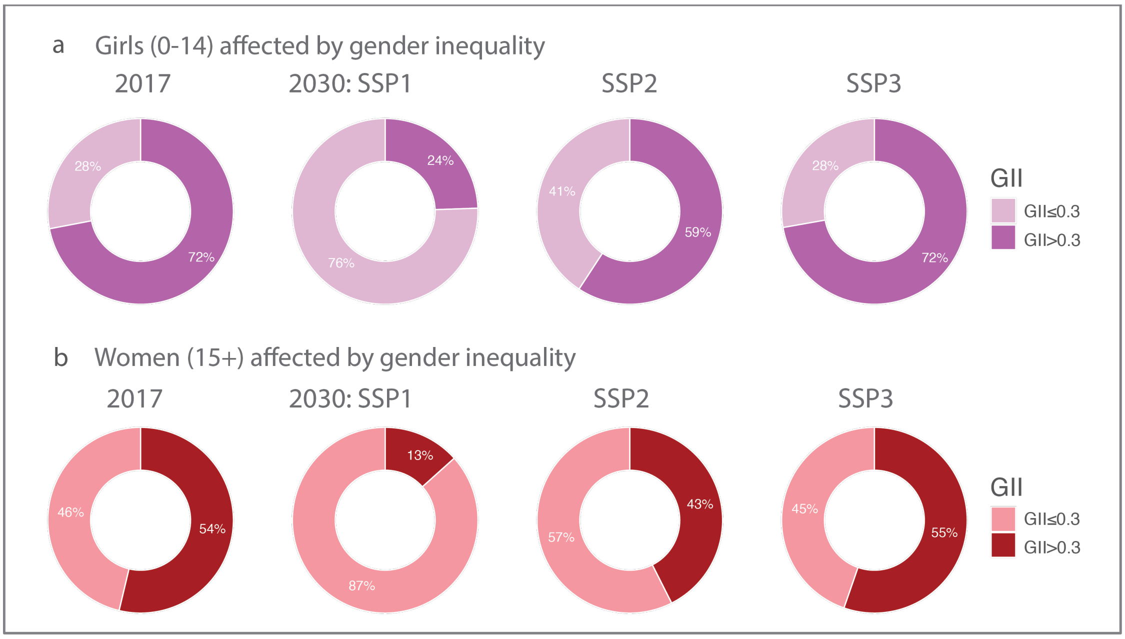

Figure 3.4: Share of women affected by gender inequality globally in 2020 and 2030. GII values for 2020 and projections for 2030 are divided in two groups. The division is based is based on the present-day range of GII in the OECD countries (0.001-0.312), which splits the countries in GII <= 0.3 and GII > 0.3. The GII estimates are coupled with population projections disaggregated by female population projections for two broad age groups: a, 0-14 years and b, older than 15.

in levels of the GII, and the importance of near-term improvements for less well-off regions. As it is the case for other indicators of socio-economic development (Crespo Cuaresma and Lutz 2015; Andrijevic, Crespo Cuaresma, et al. 2020a), the rates of improvement in the GII towards gender equality are highest up to 2050 in these scenarios. Less optimistic development pathways show a linear continuation of current trends or even a slow-down. Note that, by design, the SSPs do not allow for a systematic long-run deterioration of socio-economic indicators.

In the wider context of sustainable development – still inextricably linked to the climate change problem – the gender dimension is a crucial policy component, including as a stand-alone item under the Sustainable Development Goals (SDGs) of the United Nations' 2030 agenda. SDG 5 strives to "achieve gender equality and empower all women and girls" (UN General Assembly 2015), and the progress towards the multiple goals under SDG 5 is tracked with a set of individual indicators. The Gender Inequality Index presented here is a more holistic measure than the specific indicators used in monitoring SDG 5. With its dimensions related to reproductive health and decision-making, as well as political and employment participation, it relates to underlying structural issues determining gender inequality (United Nations 2019). As such, the GII and its projections can be a useful tool to assess how the very basic conditions for making progress on SDG 5 vary in different socioeconomic futures.

Many of the countries experiencing high levels of gender inequality are in the mid-stages of the demographic transition (Willekens 2016), implying that their populations are expected to substantially grow in the next decades. Such a demographic development exposes young women to slow improvements in health, as well as to unequal opportunities in education and employment. Given the relatively high life expectancy of women born today, the level of gender inequality they are exposed to in the next decade will affect a cohort who will shape most of the 21st century. Figure 3.4 illustrates the opportunities for near-term improvements of gender inequality: already in 2030, the fraction of young girls growing up in environments of lower gender inequality (the present-day range of the GII in OECD countries) can be more than 2.5 times larger in a pathway such as SSP1, where rates of population growth slow down and socioeconomic progress speeds up. On the other hand, scenario SSP3 virtually retains the present global distribution of our gender inequality indicator, due to faster population growth and slower and uneven socioeconomic development up to 2030. This underscores how rapid improvements towards achieving gender equality in the near-term would be possible, in line with the goals of the SDG 5. Note that for reasons of brevity we here show only scenarios 1-3, which encompass the full range of the five scenarios, and exhibit large differences between each other.

Our analysis outlines potential future gender inequality pathways under different scenarios of socio-economic development outlined in the SSPs. Our projections show that SSP1 results in major improvements in gender equality on a global scale while SSP2 shows some significant improvements but with notable exceptions in the most vulnerable regions, including Africa. In contrast, in the SSP3 world, gender inequality at the global level is either only marginally reduced or, in some cases, intensified. We show how such pathways may achieve concrete near-term improvements in the gender inequality environment for girls in the coming decade or may contribute to maintaining the status quo. The environments of gender inequality have significant implications for the growing global population, whose actions affect achievement of the SDGs. As a crucial component of adaptive capacity, gender inequality also plays a decisive role in allowing populations to adapt to increasing climate impacts. Overcoming gender inequality is a cornerstone of climate resilient development – and improvements may have far-reaching benefits for adaptation and mitigation alike. Achieving climate resilience has to be designed in a way that not only prevents further erosion of gender equality, but actively works towards it, thereby reducing vulnerability and providing an empowering environment for strengthening women's agency.

Acknowledgements

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Code availability

Code underlying the results is available at `https://github.com/marina-andrijevic/genderinequality` Data availability: GII data was obtained from the UNDP website: .Historical GDP was obtained from the Penn World Tables 7.0 (`https://www.rug.nl/ggdc/productivity/pwt/pwt-releases/pwt-7.0`) and projected values through the IIASA SSP database (`https://tntcat.iiasa.ac.at/SspDb/`). Data on educational attainment and gender equality in education is accessible through the Data Explorer of the Wittgenstein Centre for Demography and Global Human Capita.

4

Cooling gap in Shared Socioeconomic Pathways

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Abstract

The extent to which societies will globally be able to adapt to climate change is not well understood. Here we analyze socioeconomic dimensions of adaptive capacity of populations to deal with heat stress and find income, urbanization and income inequality to be important factors in explaining adaptation to heat stress with air conditioning. Using the scenario framework of the Shared Socioeconomic Pathways, we estimate the future cooling gap, which represents the difference between the population exposed to heat stress and the population with access to air conditioning. Depending on the scenario of socioeconomic development, total population affected by the cooling gap may vary between 2 billion (SSP1) and 5.2 billion (SSP3) people in 2050. Our analysis shows vast regional inequalities in adaptive capacity for one of the most universal manifestations of climate change, which underscores the need for considering of the degree of adaptive capacity in assessments of climate change impacts.

4.1 Introduction

Exposure to abnormal heat can cause various adverse effects on human health, from thermal discomfort to lethal outcomes (Gasparrini et al. 2015). Heat stress also negatively affects economic activity by reducing labor productivity (Kjellstrom et al. 2009; Burke, Hsiang, et al. 2015) as well as cognitive performance (Piil et al. 2020), but is also correlated with societal problems such as intimate partner violence (Sanz-Barbero et al. 2018), suicide (Burke, González, et al. 2018) and broader social conflicts (Hsiang et al. 2013). Impacts on human health occur through extreme events such as heat waves or droughts, but also through gradual changes in average temperatures. Recent scientific advances have attributed heat impacts on health to anthropogenic climate change (Knutson and Ploshay 2016; Harrington and Otto 2018) and there is ample evidence that these impacts will become even more prominent under more amplified global warming (Mora et al. 2017; Sherwood 2020). Heat stress becomes amplified in urban areas due to the urban heat island effect (Zhao, Lee, et al. 2014), making populations in cities additionally vulnerable. With urbanization projected to spread in all scenarios of socioeconomic development (Jiang and O'Neill 2017), this effect is expected to become even more pronounced.

A way to alleviate the impacts of heat stress is to adjust indoor temperatures with the use of a cooling device, such as a fan or an air conditioning (AC) device. However, owning a cooling device is not only dependent on exposure to climatic conditions, but also on socioeconomic factors, such as having enough income to be able to afford a cooling device. Therefore, the impact of heat stress hinges on the ability to adapt to it, and in this study we explore how the ability to adapt varies in different scenarios of future developments of societies and of climate. We are able to show how current and future inequalities in socioeconomic conditions which create differential vulnerability to climate change. Combined with exposure to climate hazards, enhances the understanding and detection of hotspots of climate impacts around the world (Byers et al. 2018).

Previous research focused mostly on modelling the effects of the uptake of cooling strategies on energy demand and implications for climate change mitigation (Isaac and van Vuuren 2009; De Cian et al. 2019; McNeil and Letschert 2008; van Ruijven, De Cian, et al. 2019). Without questioning the importance of research on future energy demand, here we take a different angle and focus instead on the adaptation aspect of cooling, understanding the access to air conditioning as a reflection of the ability of societies to adapt to the challenge of a broad conception of heat stress measured by Cooling Degree Days (CDDs).

We take the ownership of air conditioning (AC) as a proxy for adaptation, seeing it as one of the most effective implementable options on the household level and taking advantage of the fact that its implementation can be traced through census data and other country-level sources. We link the socioeconomic adaptive capacity for cooling with climate-induced need for cooling to determine the cooling gap, which expresses the difference between the population exposed to heat stress and the population with the capacity to adapt to it through the use of AC (Mastrucci et al. 2019).

Our study builds on previous research (Mastrucci et al. 2019; Isaac and van Vuuren 2009; McNeil and Letschert 2008), by providing a temporal perspective on the cooling gap over the course of the 21st century, and by using a substantially larger sample of countries and by testing for different threshold metrics of heat discomfort. Using the scenario framework of the Shared Socioeconomic Pathways (SSPs) and the Representative Concentration Pathways (RCPs), we create country-level projections of adaptive capacity to deal with heat stress and of future population exposed to heat stress.

Insights into the temporal and spatial evolution of adaptive capacity are important for better understanding of future climate impacts, yet it is disproportionally less represented in quantitative research compared to mitigation strategies and mitigation challenges. In climate impacts research, better representation of adaptative capacity and subsequently vulnerability would improve the framing of climate risk under different socioeconomic conditions (Andrijevic, Crespo Cuaresma, et al. 2020a).

Constraining the expectations of adaptation also reinforces the need for urgent and stringent mitigation and challenges the notion that adaptation and mitigation efforts can be substitutable (De Bruin, Dellink, and Tol 2009).

Within the broader spectrum of the Global Agenda for Sustainable Development, lack of access to cooling is a dimension of energy poverty that has implications for the Sustainable Development Goals (SDGs) (Khosla et al. 2020), most directly the SDG 7 on Energy Access, but through multiple economic, social and health effects of heat stress, progress towards SDGs 1 (poverty), 2 (zero hunger), 3 (good health and wellbeing), 5 (gender equality), 8 (decent work and economic growth), 10 (reduced inequalities), 11 (sustainable cities and communities) and 13 (climate action) is also made more difficult (UN General Assembly 2015; Mastrucci et al. 2019). Providing a temporal perspective on how this dimension of energy poverty evolves can inform the Agenda about what the socioeconomic conditions need to evolve in parallel or need additional policies.

Analyzing adaptation through air conditioning, however, comes with a caveat. The increased use of AC is contributing to the greenhouse gas emissions both through rising demand for electricity and through their use of refrigerants – short-lived climate pollutants such as hydrofluorocarbons (HFCs) (International Energy Agency (IEA) 2018). This in turn creates a positive feedback with climate change and the need for even more adaptation in the future. For this reason, AC is a contested adaptation option and has been termed maladaptation (Barnett and O'Neill 2010). These are important interlinkages to understand, for anticipating future energy demand and for shedding light on how large the need for adaptation will be in the future and for what must be considered in adaptation planning. However, ACs are and will continue to improve in efficiency and their refrigerants will be better controlled (International Energy Agency (IEA) 2018). Combined with low carbon electricity systems which will be widespread by the 2050s in mitigation scenarios, powering ACs may not be as consequential for emissions. Ultimately, example of the cooling gap that arises from unequal access to AC can serve as a heuristic tool to showcase adaptation gaps as a result of socioeconomically vulnerable populations exposed to increasing climate hazards.

4.2 Methods

4.2.1 AC data

In this analysis we focus only on the AC ownership at the household level. However, the stock of ACs in commercial and residential sectors is very similar and continue to grow at a similar pace (International Energy Agency (IEA) 2018). Data for AC ownership is gathered from several sources which together cover 67 countries or about 80% of the global population, a substantially larger sample than in previous research which used similar approaches. Most of the additional coverage comes from the Global Data Lab (Global Data Lab 2020) which provides subnational survey and census data on the ownership of electrical appliances, here aggregated to the national level for a cross-country analysis. The full sample covered here can be seen in Figure 4.1.

For a better overview, most of the results in the rest of this study will be presented with the countries from our sample grouped in eight geographical regions. An overview of countries in the AC sample in each region can be found in the Table C.2 in Annex C.

Cooling Degree Days (CDDs)

To calculate mean annual CDDs, we use the population-weighted (wg) average by grid cell (gi) within each country (i), of the annual sum of the positive difference between the average daily temperature and the set point temperature (Tsp):

$$CDD_i = \frac{1}{pop_{tot}} \sum_{\forall g \epsilon i} pop_g \left(\sum_{d=1}^{365} (T_{d,g} - T_{sp})^+ \right)$$

Where T_{sp} ϵ (18°C, 20°C, 22°C, 24°C) and $pop_g > 10/km^2$.

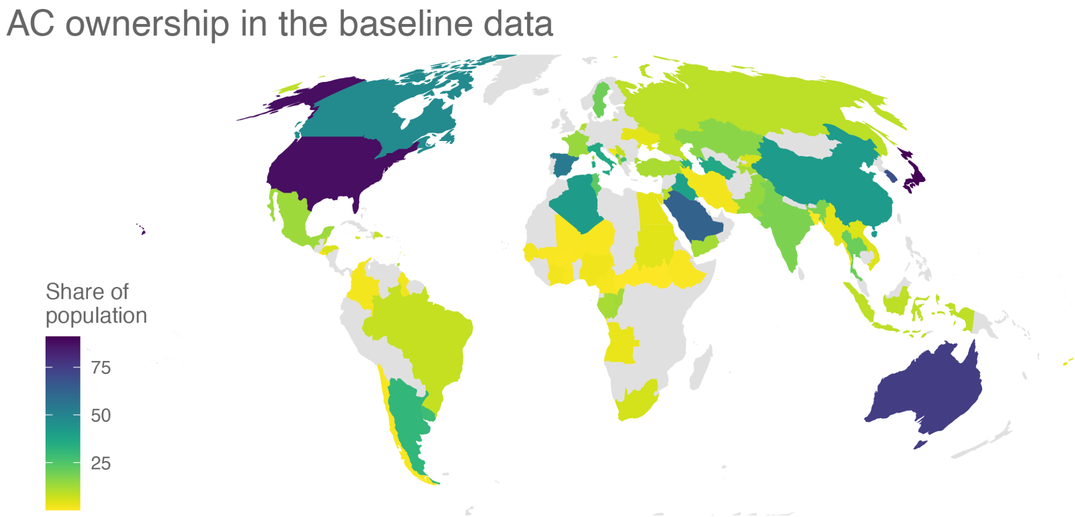


Figure 4.1: Data on AC ownership from multiple sources, used for the base specification of the statistical model.

We use gridded daily mean surface air temperature data from five CMIP5 global circulation models downscaled and bias-corrected to 0.5° (approximately 50 km at the equator) (Hempel et al. 2013). For climate scenarios we use the Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5 and RCP6.0 with respective global mean temperatures 1.7°C (1.6°C); 2°C (2.5°C) and 1.9°C (2.9°C) in 2050 (2100) (Schleussner and Mengel n.d.) higher compared to the pre-industrial level.

Mean annual cooling degree days were calculated using 21 years of data centered at each decade (2010 to 2100) to capture the gradual change in rising temperatures and smoothen out the effects of inter-annual variability. Population weighting was done using gridded population projections for the five SSPs (Jones and O'Neill 2016) similarly at decadal timesteps and 0.5° resolution.

4.2.2 Model

To estimate the future cooling gap, we combine the projections of future AC availability and future population exposed to heat stress. AC availability projections build on the two-stage modeling approach used in the seminal papers (Sailor and Pavlova 2003; Isaac and van Vuuren 2009; McNeil and Letschert 2008) that

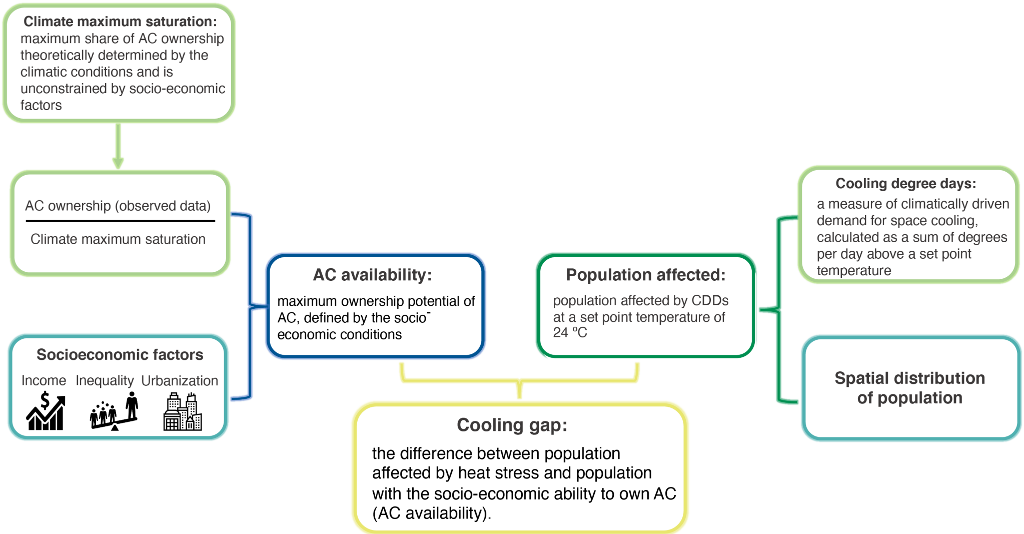


Figure 4.2: Conceptual representation of the modeling steps and explanations of key terminology.

established the relationship between AC ownership, climatic conditions and AC availability. This approach expresses AC availability as a quotient of AC ownership (actual rates of AC ownership in a given population) and a climate parameter. The climate parameter – climate maximum saturation – defines the theoretical climatic requirements for cooling, based on the energy demand for cooling that starts above a certain temperature threshold (for more detail on climate maximum saturation, see the Supplementary Material). For example, if 50% of households in a country own air conditioning, and the maximum saturation determined by the climatic conditions is also 50%, then AC is 100% available. The extent of AC availability thereby depends on the ability to own AC when needed. In previous studies, it was expressed as a function of income, which the most straightforward determinant of whether an AC device can be purchased or not. Here we add urbanization – meant to capture the increased demand for AC in urban areas (De Cian et al. 2019) – and income inequality – to reflect heterogeneity in access to energy and household appliances (Daioglou et al. 2012) – as dimensions of the socioeconomic profile that might influence the availability of AC. Key concepts and the modeling steps are summarized in Figure 4.2.

4. Cooling gap in Shared Socioeconomic Pathways

We test the conversion from AC ownership to AC availability, with four different set point temperatures (18°C, 20°C, 22°C and 24°C) that define the climate maximum saturation, and later select the regression model based on the minimum residual between the four estimates and use these country-specific temperature combinations because they improve the model accuracy and the projections.

To study the relationships between AC availability and the socioeconomic covariates we used beta regression with a logit link function, suitable for instances in which the dependent variable takes values in the interval between 0 and 1 (Cribari-Neto and Zeileis 2010). We find that in addition to using income (proxied by GDP per capita), urbanization and inequality as socioeconomic covariates enhance the explanatory power of the regression model. Regression results are provided in Table C.1 in Annex C.

The statistical model for the observational period rests on the following equation:

$$AC\ Availability_{i,t} = \beta_0 + \beta_1 GDP_{i,t} + \beta_2 Inequality_{i,t} + \beta_3 Urbanization_{i,t} + \varepsilon_{i,t}$$

Coefficient estimates obtained from the beta regression model are imposed on projections of GDP (Crespo Cuaresma 2017), inequality (Rao et al. 2018) and urbanization (Jiang and O'Neill 2017) which, based on the same equation, calculate future values of AC availability in the scenario framework of Shared Socioeconomic Pathways (SSPs), a commonly used set of scenarios of future socioeconomic development (O'Neill, Kriegler, et al. 2017) (detailed descriptions of each scenario can be found in the Supplementary Material).

Population exposed to heat stress is calculated by coupling the estimates of population weighted CDDs, with population projections to estimate future exposure to heat stress. The set point temperature used to estimate population exposed to heat stress is 24°C, which was the temperature at which the residual was the smallest for most countries in the regression analyses used above (see Figure C.2. in Annex C). Then, we calculate populations in areas with at least 50, 100, 200 and 400 CDDs, and define the exposed population as the median value. Uncertainties of the different temperature thresholds and counts of CDDs can be seen in the see Figure C.3. in Annex C, together with several representative countries falling into a given temperature-count bracket.

Finally, to calculate the cooling gap, we calculate the difference between population exposed to heat stress and the share of population with access to AC (AC availability):

$$Cooling\ gap = Population\ exposed\ to\ heat\ stress\ \times (1\ -\ AC\ Availability)$$

Limiting the estimates to this upper bound of tested temperatures is a conservative approach, compared to the previous research which typically takes the daily mean temperature as the temperature threshold for cooling 18°C (Isaac and van Vuuren 2009; Davis and Gertler 2015), meaning the estimates of heat exposure would be even higher if we considered areas where cooling is demanded at lower CDD thresholds.

It should be noted, however, that many different metrics of heat stress can be found in research. A large body of work has dealt with the impacts of extreme heat stress (e.g. heat waves) (Andrews et al. 2018; Diffenbaugh et al. 2007; Dahl et al. 2019; Zhao, Lee, et al. 2014), which can have more adverse and more severe impacts on human health than the heat stress metric that is underlying this analysis. This means that the conception of heat stress here spans thermal discomfort that can be alleviated with “mild” air conditioning and severe heat stress that requires, for example, the AC to run overnight. For estimates of energy demand, it is important to understand the intensity and the duration of the AC use, but our analysis focuses on whether people have access to AC and thereby our definition of heat stress can be more flexible. Accounting for other parameters that determine the severity of heat stress, such as the deviation from the monthly mean, humidity, number of consecutive days of heat stress or the diurnal period (i.e. difference between daily maximum and daily minimum temperature which would allow for insights on the recovery period from heat) would nevertheless be a valuable contribution in future applications.

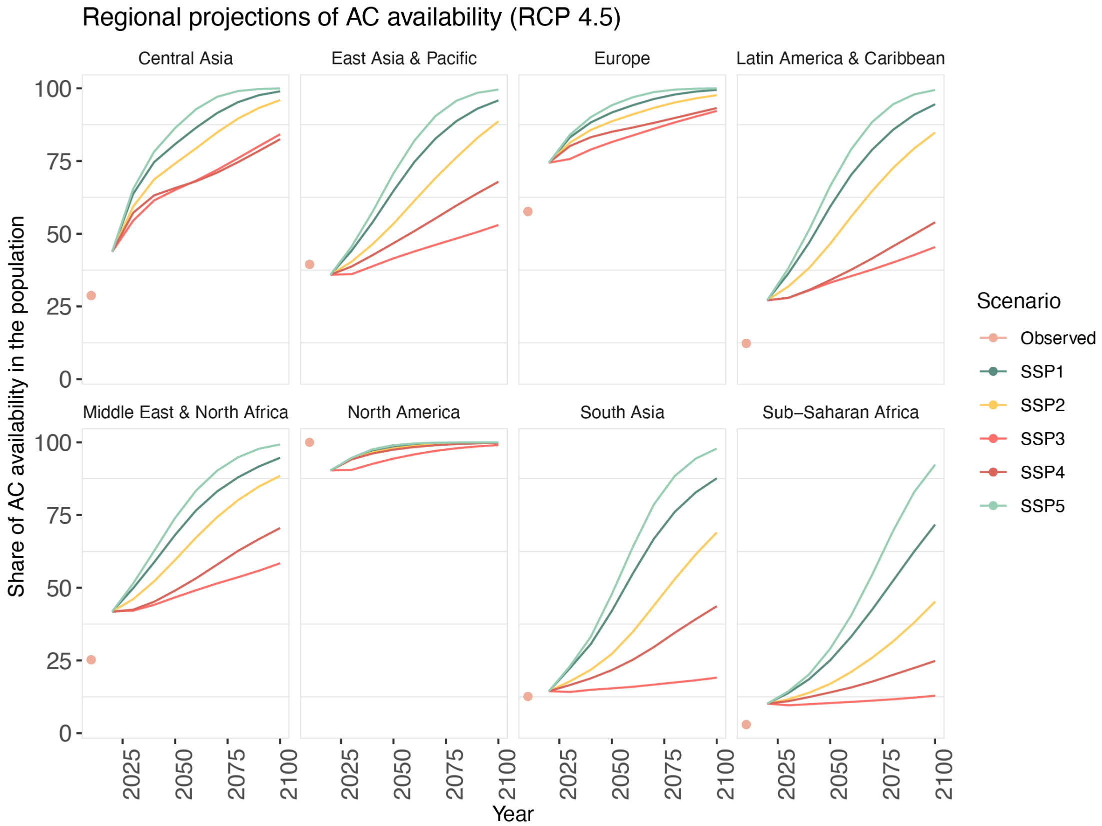


Figure 4.3: Observed and projected rates of AC availability for eight large geographical regions.

4.3 Results and discussion

4.3.1 AC availability

Figure 4.3 shows the projections of future AC availability, with country-level estimates averaged on the level of eight geographical regions, and with RCP 4.5 - the central scenario used throughout the analysis. High AC availability reflects high levels of income and urbanization and on average low levels of income inequality.

North America is the only region that displays 100% AC availability, followed by Europe at about 60%. Both of these regions display little scenario difference in their future AC availability, implying that adaptive capacity to use AC against heat stress is high, and will remain high in the future in the scenarios that we considered here. The other six regions differ substantially in the degree of scenario dependence. The difference is the largest for South Asia and Sub-Saharan Africa, which in scenarios of low and sluggish socioeconomic development (SSP3 and 4) see a stagnation or a marginal increase to about 25% of AC availability by the end of the century, in the middle-of-the-road scenario SSP2 reach about 60% and 40% respectively by 2100, and in scenarios of fast socioeconomic developments, reach saturation rates between 75% and 100% over the same time period. East Asia and the Pacific, Latin America and the Caribbean, Middle East and North Africa also display scenario differences, with about a 50-percentage point spread between scenarios at the end of the century. AC availability in Central Asia is expected to increase in all scenarios, with difference in 2100 between the "worst" and "best" case scenario of 25 percentage points.

4.3.2 Heat stress exposure

Figure 4.4 shows estimates of heat stress used to calculate cooling gap. Already today, the population in the Southern Hemisphere is disproportionally affected by heat stress, with much of the Sahel region, Sub-Saharan Africa and most of South Asia having over three quarters of their populations exposed to heat stress.

Going towards mid-century in mid-range scenarios for both population growth and climate (SSP2 and RCP 4.5), increasing shares of population in the northern hemisphere are affected, and in 2100, almost entire populations in all countries except for Scandinavia and Great Britain are exposed to some sort of heat stress and heat discomfort in these two scenarios. Uncertainties in the climate scenario for 2050 and 2100 for RCPs 2.6 and 6.0 are available in the Figure C.5 in Annex C.

4.3.3 Cooling gap projections

Figure 4.5 shows the absolute population affected by cooling gap – i.e. people exposed to heat stress, but without access to it. We focus on two time slices: mid-century and end of century, for emissions scenario RCP 4.5 and SSPs 1-3 which span the entire range of estimates (for paucity we show only three scenarios). In 2050, South Asia stands out as a region with the largest population affected by cooling gap, with the scenario spread between 750 million people affected in

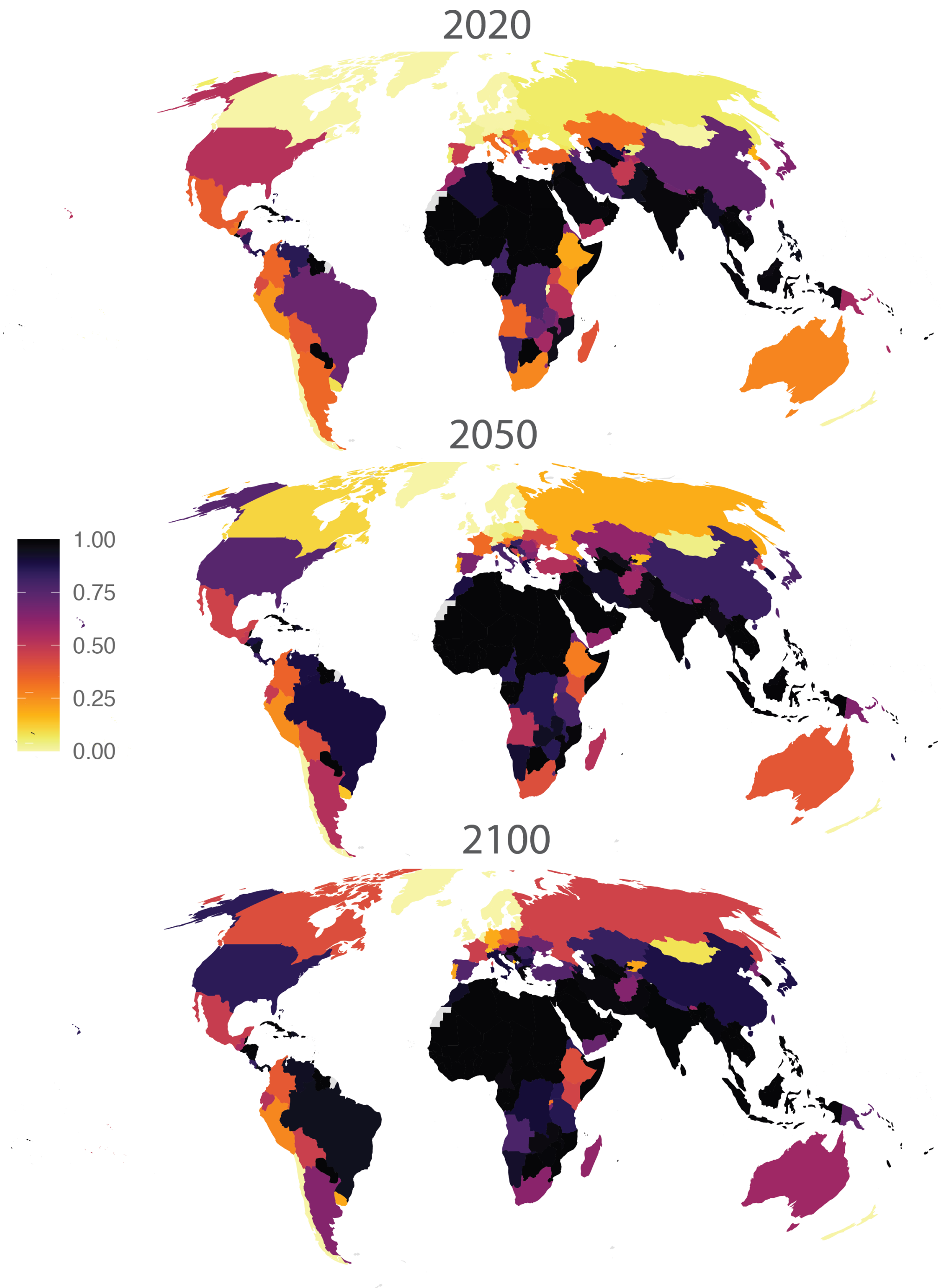
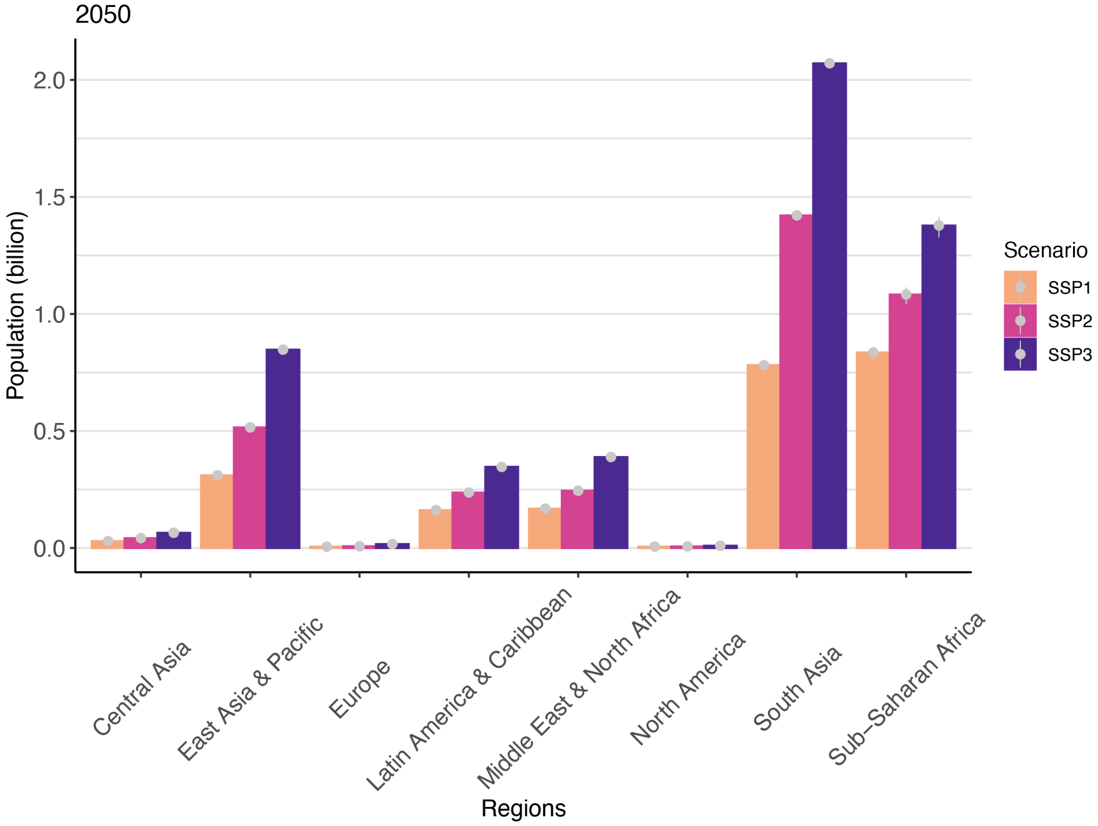


Figure 4.4: Population exposed to heat stress measured by CDDs above the set point temperature of 24°C in 2020, 2050 and 2100. Increase in population is based on SSP2 scenario and CDDs increase is in RCP 4.5.

SSP1 and over 2 billion people affected in SSP3. The second most affected region is Sub-Saharan Africa, followed by East Asia & Pacific. By the year 2100, the number of people affected by cooling gap substantially reduces for scenario of fast socioeconomic development (SSP 1) and reduces to a medium degree in the scenario of largely continuing the current development trends (SSP 2). Meanwhile, population affected drastically increases in SSP3 – a scenario of fast population growth and slow socioeconomic development – reaching almost 3 billion in South Asia and 2.5 billion in Sub-Saharan Africa.

When the cooling gap is regarded in relation to the total population of these regions (Figure 4.6), the picture becomes different, with Sub-Saharan Africa now having the highest shares of population affected by cooling gap across all but the worst scenario and in both time periods. The region affected the least is North America. As shown on Figure 4.4, North America already is and is projected remain largely unconstrained in terms of its adaptive capacity to heat stress, and its population is projected to stagnate or even shrink in most scenarios. In the worlds of SSP3, almost 80% of people in South Asia and 70% Sub-Saharan Africa would be exposed to heat stress without the adaptive capacity to deal with it, both in mid-century and in the long run. The access to AC can be improved by mid-century in scenarios of faster income growth, urbanization, reduced inequality and slower population growth, but only at the end of the century these regions are projected to display similar levels of cooling gap to today's rich countries of Europe and North America. Somewhat smaller, but still substantial portions of people are going to be affected in these scenarios also in Latin America and the Caribbean, and in the Middle East and North Africa regions. Significant improvements can be brought about in the SSP1 pathways, but only towards the end of the century.

Figures 4.5 and 4.6 also show the spread of estimates across the three RCP scenarios. As noted earlier in the section on heat stress exposure, the metric used here is generally not very sensitive to the climate scenario, but some regions still display differences up to 10 percentage points. Because of the nature of the three RCP scenarios used here which do not markedly differ until later in the century,



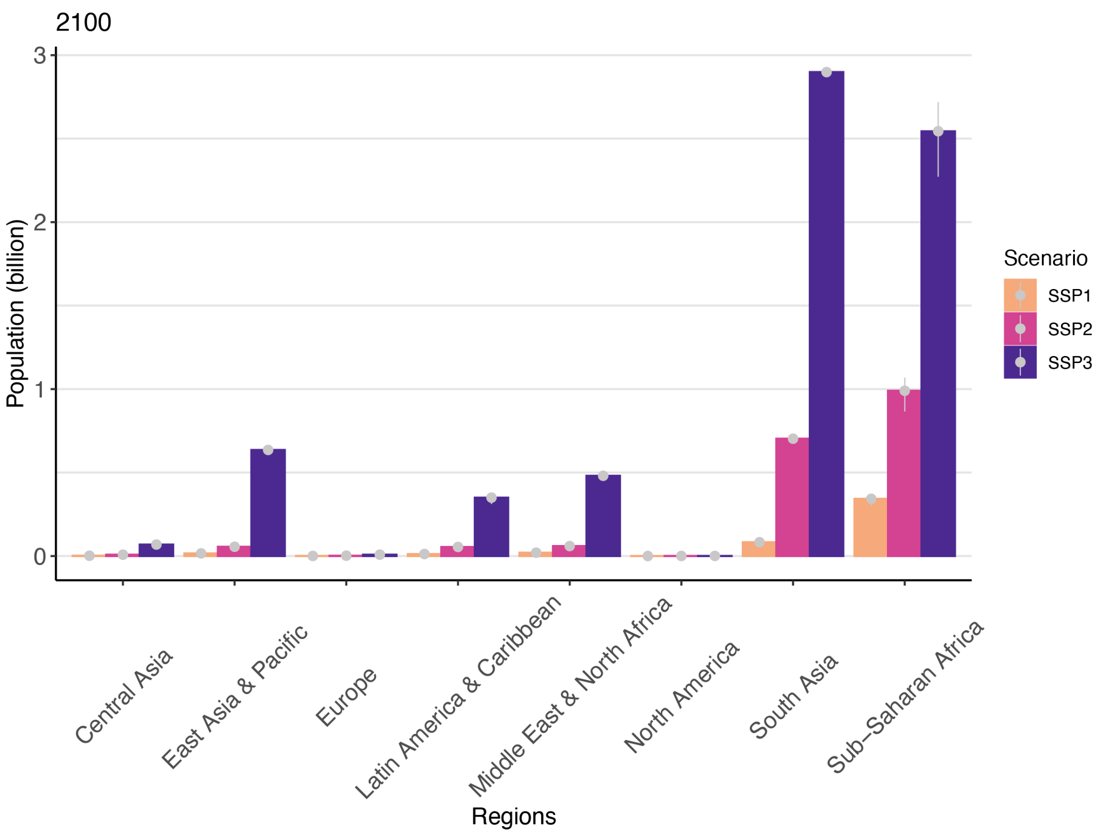


Figure 4.5: Absolute population estimates affected by cooling gap in 2050 and 2100. The central estimate for heat stress is based on RCP4.5, and the whiskers indicate the spread of the emissions scenarios. The bars are grouped in eight geographical regions and shown for three SSP scenarios.

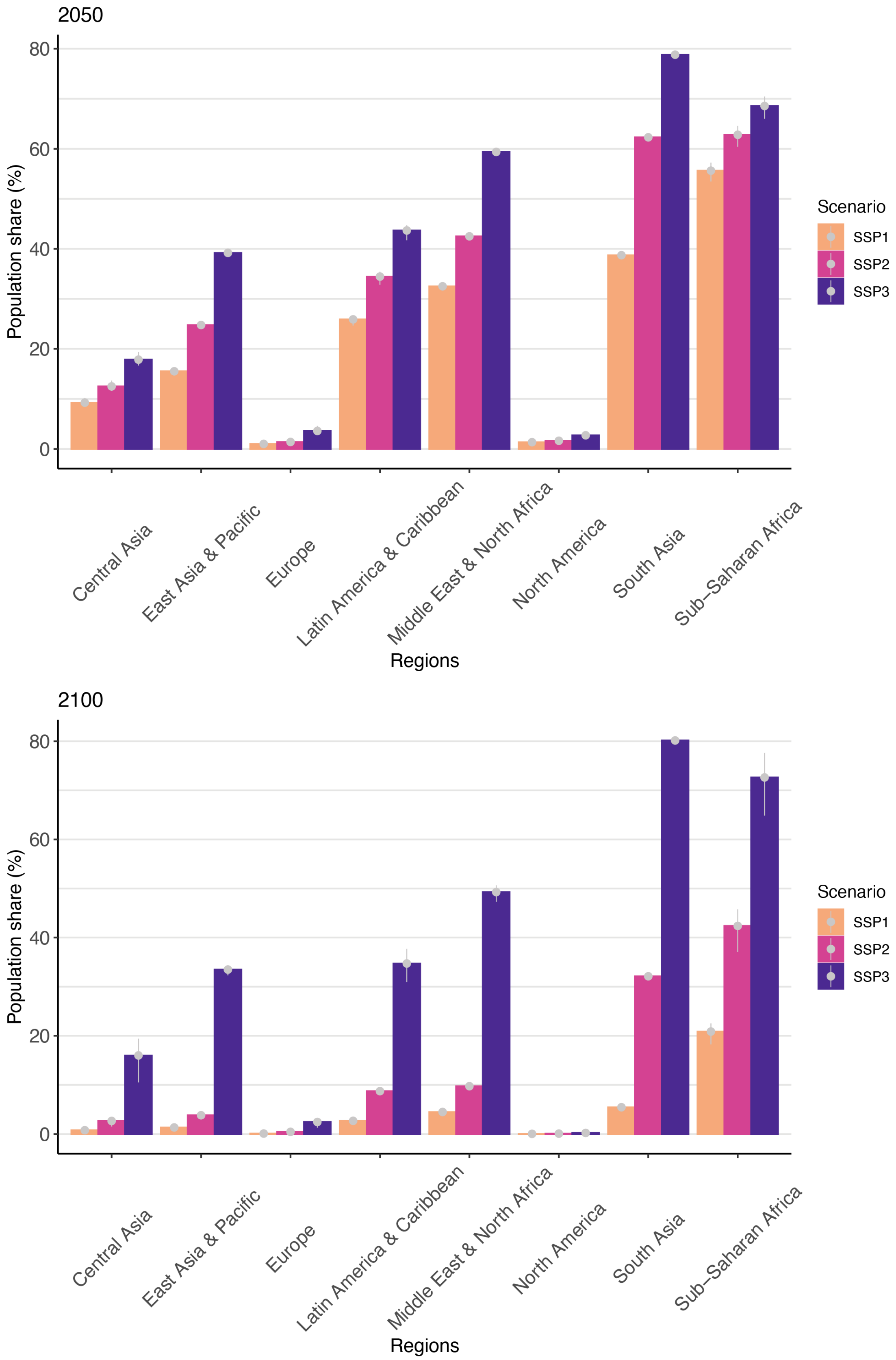


Figure 4.6: Share of population affected by cooling gap in 2050 and 2100. The central estimate for heat stress is based on RCP4.5, and the whiskers indicate the spread of the emissions scenarios. The bars are grouped in eight geographical regions and shown for each of three SSP scenarios.

the climate signals become significantly pronounced only later, which is the reason for seeing more visible impacts of the different emissions scenario only on graphs for 2100. However, for the most affected regions of Central Asia and Sub-Saharan Africa, the way we measure heat stress makes very little difference to the outcomes in terms of population affected because these locations already face high exposure.

This independence from the climatological component should be interpreted with caution, because it does not speak to the more severe impacts of heat extremes that are projected to occur already at 2°C global mean temperature increase above the pre-industrial period, though could be dampened if the warming is limited to the Paris Agreement goal of 1.5°C (Schleussner, Lissner, et al. 2016). Nevertheless, the CDD metric used for estimating heat exposure here reflects the need for AC in a broad sense and while this need might become more pressing in the future, we are not able to assess how pressing it will become depending on the level of warming, but merely that it is there and that populations will seek for adjusting their thermal comfort.

Even though the most affected regions here are consistently in the Southern Hemisphere, previous research finds that a growing number of households in Europe is struggling to meet their needs for cooling (Thomson et al. 2019), and the same might hold for North America despite its consistently high estimates of AC availability. This finding will become more pertinent with higher rates of people living in cities (Jones, Tebaldi, et al. 2018). Spatial resolution of our research does not allow for analyses on that level, but it is important to keep in mind that even in the regions portrayed here as best-off, there could still be portions of populations affected by cooling gap or energy poverty in a broader sense.

This analysis could be further elaborated upon with several additional considerations. Firstly, although we cover – to our best knowledge – the biggest sample of country-level data on AC saturation, 67 countries are far from a full global coverage which would yield even more precise estimates. Secondly, we consider only one type of cooling option, whereas other devices such as fans are also used for cooling. Third, the use of CDDs to measure heat stress exposure has its shortcomings. CDDs do not allow for a distinction between thermal comfort demands by people who want

AC without severe risks of heat stress and people who need AC to survive. Also, CDDs increase linearly with population, which ignores the variation household sizes around the world (Biardeau et al. 2020). This metric also does not account for differences in building standards and types, as better quality of insulation reduces need for indoor cooling (De Cian et al. 2019). Lastly, physiological adaptation of the body to heat stress is evident in people in hotter climates being less sensitive to high temperatures (Zhao, Ducharne, et al. 2015), and this can be expected to take place to some extent in the future as well. Future research could tackle these shortcomings by using different heat stress metrics, or consider heat extremes and their duration which would also have disproportionately negative effects on the poor (Ahmadalipour et al. 2019).

4.4 Conclusion

The perspective of adaptive capacity as a function of different socioeconomic factors is an important consideration for future projections of impacts of climate change, which currently do not explicitly account for whether there is a potential for adaptation in the first place. This study presents a toolkit for analyzing adaptive capacity across countries and over time regarding AC use as an adaptation option for coping with heat stress. Our analysis improves over earlier research that uses only income as a predictor of AC availability by regressing AC availability on income, urbanization and income inequality.

Based on the future trajectories of income, income inequality and urbanization, we here show future estimates of AC availability, to reflect the adaptive capacity to deal with heat stress. By coupling these projections with estimates of future heat stress based on exposure to CDDs, we produce estimates of the future cooling gap. Our projections show little dependence on the climate scenario or heat stress threshold temperatures considered here, and the size of the gap between population that needs AC for adjust their thermal comfort and the population able to afford AC predominantly depends on the scenario of socioeconomic development (including population growth) which is reflected in the large range between the scenario estimates. Between the scenario of low challenges to adaptation and mitigation (SSP1) and the scenario with high challenges to adaptation and mitigation (SSP3) total population affected by the cooling gap globally could vary between 2 to 5.2 billion people in 2050, and between 0.2 and 7.2 billion in 2100 (see Figure C.4 in Annex C). Future adaptive capacity in countries in the Global South depends greatly on the socioeconomic dynamics or factors such as income, urbanization and inequality, while the developed countries of the sample in this instance only show dependence on the climatic conditions.

These estimates of the future cooling gap point at vast regional inequality in future adaptive capacity, in all but most progressive scenarios of socioeconomic development. Even in the most optimistic scenarios of the SSP framework, some of the vulnerable regions will not reach the same levels as in rich countries. As an important dimension of energy poverty, the extent of cooling gap and its scenarios presented here can be used for informing the attainability of sustainable development pathways of the different SDGs that depends on the broader socioeconomic dynamics.

The need to adapt to climate change is already apparent and will only become more pressing in the future. Our analysis shows that fast population growth that is not followed by socioeconomic development would expose more than three quarters of populations to unabated heat stress in some of the world's most populous regions, like South Asia, Sub-Saharan Africa and Latin America. The degree to which societies will be able to adapt in the future needs to be elucidated, in order to understand climate impacts better. This will help us avoid overestimating of the potential of adaptation and underestimating of the urgency of mitigation.

5

Scenarios of sustainable irrigation expansion in the 21st century

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Abstract

Irrigation expansion onto rainfed croplands is an important part of the portfolio of agricultural measures, contributing to a more resilient crop production while enhancing agricultural yields. Existing global assessments of irrigation illustrate the biophysical potential, but generally do not account for socioeconomic and environmental constraints to irrigation deployment. Here we provide scenarios of regionalized sustainable irrigation expansion linked to socioeconomic projections from the Shared Socioeconomic Pathways framework, while accounting for biophysical irrigation limits. Under a Sustainability scenario, we find that sustainable irrigation could feed 2 billion people globally by 2100. With an additional 90 million people, sub-Saharan Africa is the region with the highest percentage increase in people fed via sustainable irrigation deployment. However, even under the most optimistic scenarios only half of the theoretically possible global biophysical irrigation potential would be utilized after accounting for socioeconomic constraints. Our results highlight the need for appropriate representation of socioeconomic factors in scenarios of future irrigation deployment.

5.1 Introduction

More than 800 million people are currently chronically undernourished (United Nations 2018). To meet the global increase in food demand, which is mainly driven by population and income growth, projections suggest that current global crop production needs to at least double by 2050 (Beltran-Peña et al. 2020). Most agriculture is currently rain-fed, but climate change is expected to change rainfall patterns and further exacerbate existing water- and heat-stress. Irrigation expansion, despite its documented caveats (Foster et al. 2018; Pulido-Bosch et al. 2018), plays an essential part in the portfolio of response options by offering the possibility to increase crop yields via the maintenance of reliable water supply, while potentially also alleviating biogeophysical effects on temperature extremes (Rosa, Chiarelli, Rulli, et al. 2020). Irrigation will also have an important role in the sustainable intensification of agriculture, an effort to halt agricultural expansion by increasing crop yields over underperforming cultivated lands (Mueller et al. 2012). However, half of global irrigation practices are unsustainable because they are depleting freshwater stocks and impairing environmental flows (Rosa, Chiarelli, Tu, et al. 2019) (Box 1). Recent global studies assessed biophysical constraints to sustainable irrigation and found that global rain-fed croplands hold significant potential for sustainable irrigation expansion because water will likely be available to suffice irrigation water demand without depleting environmental flows and freshwater stocks (Rosa, Rulli, et al. 2018; Beltran-Peña et al. 2020). These studies find that around 2.4 billion people are currently being fed via irrigation – half of it unsustainably (Rosa, Rulli, et al. 2018). If the biophysical potential for sustainable irrigation was to be exhausted, a total of 4 billion people could be fed via the calories that could potentially be produced (Rosa, Rulli, et al. 2018). The analyses focused on hydrological limits to irrigation expansion onto rain-fed croplands, without accounting for other socioeconomic factors that might also influence irrigation expansion potentials. Yet, in over 25% of global rain-fed croplands, irrigation is limited by institutional and economic capacity instead of hydrologic constraints, a condition known as agricultural economic water scarcity (Rosa, Chiarelli, Rulli, et al. 2020). In fact, social, political, and economic factors will ultimately influence future irrigation development. Therefore, there is a pressing need to couple biophysical assessments of irrigation expansion potential with socioeconomic projections to identify future target regions for sustainable intensification of agriculture through irrigation expansion.

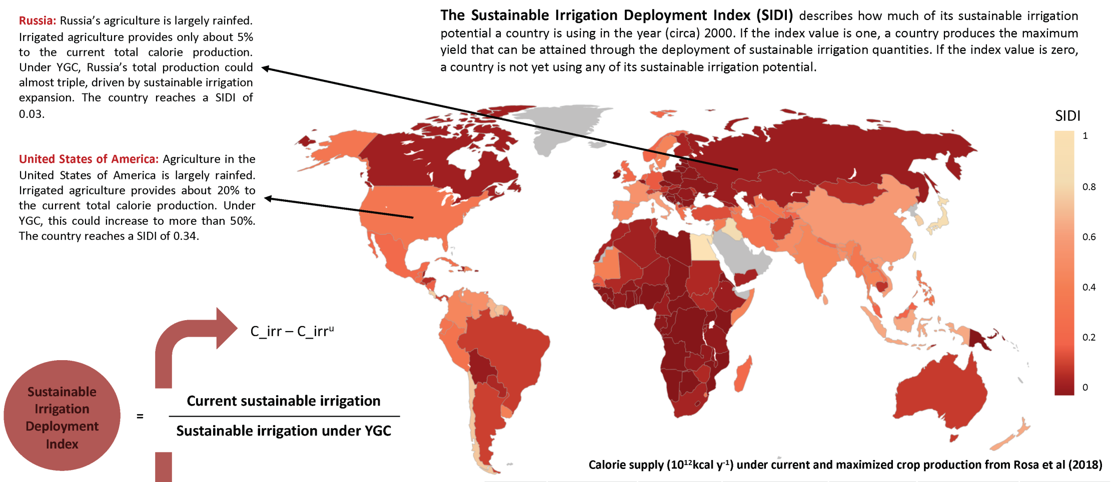
In this study we assess the irrigation crop yield gap – the difference between the actual crop yield and the maximum potential yield that could be achieved by deploying sustainable irrigation (Mueller et al. 2012). To study how the current deployment of sustainable irrigation varies across countries and over time, we introduce the Sustainable Irrigation Deployment Index (SIDI), which indicates how much of its domestic sustainable irrigation potential a country is currently using in comparison to what could be possible under maximum sustainable irrigation. We assume that the extent to which the yield gap can be closed by deploying sustainable irrigation depends on the societal ability to do so (we refer to this property as adaptive capacity), which in turn is a product of various socioeconomic resources such as governance (Klein et al. 2014). By determining which socioeconomic factors enable or hinder the implementation of sustainable irrigation in the agricultural sector, we are able to holistically project sustainable irrigation deployment alongside the Shared Socioeconomic Pathways (SSPs) (O'Neill, Kriegler, et al. 2017) throughout the 21st century (Box 1). It is important to understand the factors that enable or hinder the deployment of sustainable irrigation, as well as the temporal dimension of those factors. Thus far, these socioeconomic factors remain overlooked in assessments of potential future irrigation deployment, including climate impact models, which tend to assume optimal or maximum possible irrigation and thereby overstate its benefits (Holman et al. 2019).

5.2 The Sustainable Irrigation Deployment Index

The SIDI is defined as the ratio between the current sustainably irrigated calorie production and the maximum potential yield that could be attained at yield gap closure (YGC) by deploying sustainable irrigation (see Figure 5.1 and Methods section for more detail). Typically, maximum potential yield is defined as the yield of a crop cultivar when it is grown in an environment with non-limiting water and nutrient supplies, sufficient light and no pests or diseases (Evans and Fischer 1999). While progress in technology has allowed for large quantities of nitrogen fertilizers to be produced, water still remains a critical input limiting food production (Rosa, Chiarelli, Rulli, et al. 2020). Therefore, we here consider the yield gap attributable to a crop water deficit but for the sake of simplicity, we use yield gap closure (YGC) to refer to a scenario where no water limitation is prevalent. The yield gap is considered closed when there is no difference between potential sustainable irrigation and the actual sustainable irrigation of countries (Rosa, Rulli, et al. 2018). We build on previous estimates of the sustainable irrigation potential under current conditions and a scenario of YGC (Rosa, Rulli, et al. 2018). The SIDI by design informs on the potential for sustainable irrigation deployment, which should not be interpreted as a measure of the share of sustainable versus unsustainable irrigation in a country at a given point in time (see Figure D.2 in Annex D).

5.3 The SIDI in a socioeconomic context

Quantitative assessments of irrigation deployment have been of high interest in the scientific community (Nachtergaele et al. 2020; Puy et al. 2020; Rost et al. 2009; Jägermeyr et al. 2017; Faurès et al. 2002). Existing efforts to assess the future implementation of sustainable irrigation were mainly focused on biophysical factors by quantifying irrigation water requirements using climate, water or irrigation models, or on the influence of future technological advancements according to various scenarios (Döll and Siebert 2002; Hurtt et al. 2020; Graham et al. 2018;

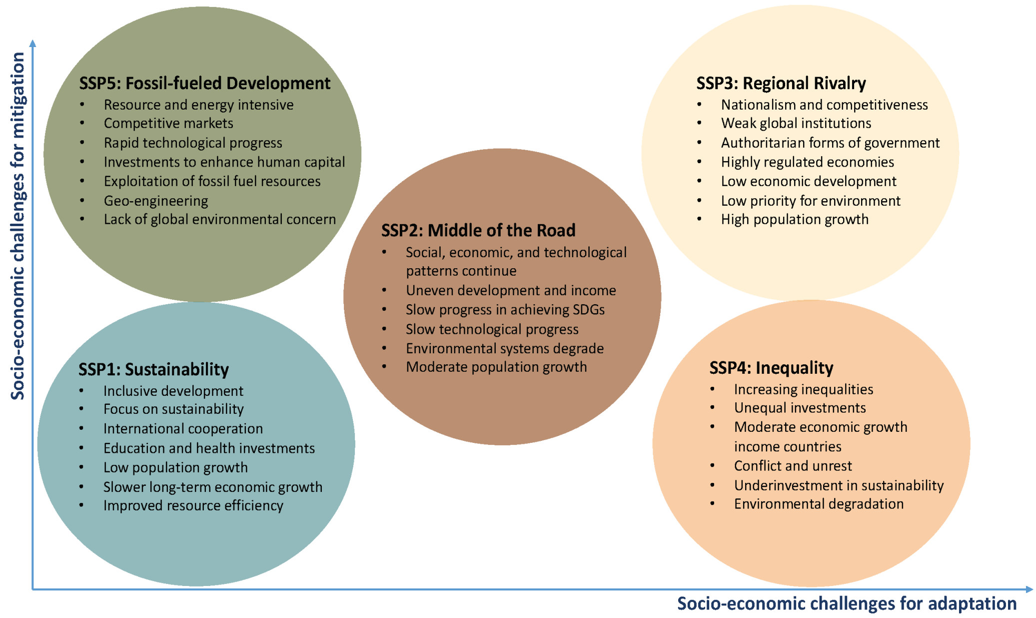


SIDI	Country	C_r	C_irr	C_irr^u	YGC_irr	YGC_irr^u
0.34	USA	130.6	24.3	14.6	62.7	19.9
0.03	Russia	26.1	1.2	0.1	39.3	10.9

Figure 5.1: A conceptual framework of the Sustainable Irrigation Deployment Index. The formula of the index is displayed on the bottom left. We provide example input data from Rosa et al. (2018) for Russia and the United States of America because of their importance in global food production, to illustrate the components of the SIDI. The map shows the SIDI per country calculated with observed data from (circa) 2000.

Beltran-Peña et al. 2020; Rosa, Rulli, et al. 2018). However, they do not account for country-specific socioeconomic conditions that, as key determinants of adaptive capacity, will enable or preclude irrigation deployment (Klein et al. 2014). Moreover, some of the existing studies do not take into consideration the biophysical constraints for irrigation (e.g., (Hurtt et al. 2020)). Our study differs from existing analyses, as the focus is on assessing how socioeconomic variables (embedded within the SSP framework) will constrain or limit the biophysically sustainable irrigation potential. In order to comprehend and isolate these socioeconomic drivers to irrigation expansion, and to reduce further uncertainty related to projected climate impacts, we refrain from additionally including the effects of climate change on water availability and demand for irrigation in this study (Rosa, Chiarelli, Rulli, et al. 2020).

We embed the SIDI in the framework of the Shared Socioeconomic Pathways, five broad narrative-based scenarios of future socioeconomic developments (Figure 5.2). These scenarios have been developed as baseline trajectories for use in integrated assessments of climate change and socieconomic developments. The five SSPs span a



b

Irrigated agriculture: the artificial application of water from surface water bodies and aquifers to croplands. Irrigation ensures crop growth under non-water limiting conditions, therefore increasing crops productivity
Unsustainable irrigation: when water consumption for irrigation is higher than local water availability causing loss of environmental flows and depletion of freshwater stocks
Rain-fed agriculture: farming that depends solely on rainwater and no irrigation water is applied
Sustainable irrigation expansion onto rain-fed croplands: agricultural adaptation measure to reduce water stress and improve yields
Crop yield gaps: the difference between maximum attainable yield and the yield that is currently achieved
Agricultural intensification: measures to increase crop yields over currently underperforming cultivated lands
Environmental flows: the quantity, timing and quality of water flows required to sustain freshwater ecosystems
Adaptive capacity: the ability of systems, institutions, humans, and other organisms to adjust to potential damage, take advantages of opportunities, or respond to consequences of climate change

Figure 5.2: The Shared Socioeconomic Pathways and concepts and definitions about agriculture and irrigation. (a) Narratives of distinct socioeconomic futures over the 21st century. The framework provides quantitative adaptation-relevant projections for population, education, urbanization, income, the Human Development Index, inequality, governance and gender inequality. (b) Concepts and definitions of irrigated agriculture, unsustainable irrigation8, rain-fed agriculture, sustainable irrigation expansion, crop yield gaps, agricultural intensification, environmental flows and adaptive capaicty.

a wide range of futures in terms of the socioeconomic challenges they imply for mitigation and adaptation (O'Neill, Kriegler, et al. 2017). The SSPs serve as a basis for quantification of some of the key dimensions of the scenarios. Here we utilize this framework to calculate projections of potential sustainable irrigation expansion under socioeconomic change.

We test for different quantified socioeconomic dimensions of the SSPs to identify those that explain variations across countries in the current level of sustainable irrigation deployment, as proxied by the SIDI (see Tab. S2). Using a cross-sectional regression with SIDI as the dependent variable, socioeconomic determinants as independent variables, and controlling for the share of rain-fed crops in the total production, we find that governance (Kaufmann 2010) shows a significant relationship with the SIDI (see Methods). The share in current rain-fed agriculture (compared to the total sustainable calorie production) is expectedly relevant for the level of sustainable irrigation deployment, indicating that countries in which a high fraction of calorie production is currently met by rain-fed agriculture have implemented sustainable irrigation to a lesser extent. From a hydrological point of view, rainfed agriculture is also regarded as being sustainable, however, we assume it to be less resilient in the light of climate change. The significance of governance, on the other hand, indicates that countries with better institutions, less corruption and better regulatory quality (to name a few characteristics of what constitutes "good governance" according to the employed indicator (Andrijevic, Crespo Cuaresma, et al. 2020a) are also closer to their maximum sustainable crop yields. These relationships neither imply causation, nor does it imply that good governance is the only driver of sustainable irrigation deployment. Our aim is to identify a statistical relationship that allows for an internally-consistent temporal extension of the SIDI within the SSP framework. GDP was also detected to have an effect on the current variation of the SIDI, but it becomes insignificant after the indicator of governance is introduced. The two identified predictors, namely the level of governance and the share of rainfed agriculture, are able to explain more than 70% in the current variations in used sustainable irrigation potential across the globe (Tab. S2).

5.4 Methods

The Sustainable Irrigation Deployment Index (SIDI) builds on previous work by Rosa et al. (2018). We use the data estimates of calorie production under current conditions and in the case of maximized crop production by alleviation of water limitations (called the yield gap closure, or YGC scenario). Using a global process-based crop water model (Chiarelli et al. 2020), Rosa et al. (2018) assessed crop water requirements to reach yield gap closure, i.e. the amount of irrigation water needed to complement input from precipitation so as to ensure sufficiently high soil moisture levels and satisfy the crop evapotranspirative demand. They used spatially distributed information on rain-fed/irrigated yields and harvested areas in year 2000 from Monfreda et al. (2008) and Portmann et al (2010), respectively. They first calculated evapotranspiration for each day, crop and grid cell for both rainfed and irrigated cases. The daily irrigation water requirements to reach YGC were then calculated as the difference between the two, and aggregated over a year. They compared the irrigation water demand to local renewable freshwater availability (for both human water use and environmental flows) to identify regions of the world where irrigation can be expanded into currently rain-fed croplands without threatening freshwater ecosystems and depleting freshwater stocks. The analysis was conducted at the pixel level, we aggregated their results to the country- and region-level.

5.4.1 The Sustainable Irrigation Deployment Index

We derive the calories that are currently produced via sustainable irrigation from the estimates of Rosa et al. (2018) of total calories produced via irrigation as well as their unsustainable share in 2000 (see Equation 1 and Tab. S1). We then use their estimates of total irrigation calories produced via irrigation under a yield gap closure scenario (C_{irr}), the additional calories that would be produced via unsustainable expansion or intensification under YGC (C_{irru}) and the calories currently produced via unsustainable irrigation (C_{irru}) to assess the potential gain under YGC by implementing sustainable irrigation (Equation 2). The amount of calories produced under YGC also includes those being currently produced. All estimates are reported in 1015 kcal per year, the full table can be found in the Annex D (Table D.1).

$$Current\ sustainable\ irrigation = C_{irr} \breve{\ } C_{irr}^{u}$$

$$Sustainable\ irrigation\ under\ YGC = YGC_{irr} \breve{\ } YGC_{irr}^{u} \breve{\ } C_{irr}^{u}$$

The SIDI is then derived following:

$$Sustainable\ irrigation\ deployment\ index\ (SIDI) = \frac{Current\ sustainable\ irrigation}{Sustainable\ irrigation\ under\ YGC}$$

5.4.2 Linear model of the present-day SIDI

After deriving the SIDI for each country under current conditions, we calculated the mean GDP (Crespo Cuaresma 2017; Dellink et al. 2017; Leimbach et al. 2017), population (KC and Lutz 2017), urbanization (Jiang and O'Neill 2017), and governance (Andrijevic, Crespo Cuaresma, et al. 2020a) over the 1995-2005 time period. Our approach aims to explain between-country variation in the SIDI with a linear regression model using the above-mentioned socioeconomic variables as predictors. Details on the coefficients and significance associated with each variable are included in the supplementary materials (Tab. S2). Our final model specification expresses SIDI as a function of the share of calories produced via rain-fed agriculture ($Share\ rainfed$) and $governance$:

$$SIDI_{i,t} = \beta_0 + \beta_1 Share\ rainfed_{i,t} + \beta_2 Governance_{i,t} + \varepsilon_{i,t}$$

where i denotes country, t denotes time (year), β_0 is the intercept, coefficients β_1 and β_2 are the coefficient estimates for the covariates and $\varepsilon_{i,t}$ is the robust standard error.

5.4.3 SIDI projections.

Keeping the β coefficients constant, we derive projections for the SIDI by using estimates of the future evolution of the governance index for each of the five SSP scenarios (see Table D.2 in Annex D), as well as computing that of the future share of rain-fed agriculture for every 5 years. Future governance estimates are available until 2095, therefore our projections also end in this year.

Governance projections were unavailable for some countries, which were thus removed from the analysis: Angola, Afghanistan, Albania, Myanmar, Montenegro, State of Palestine, Timor-Leste and China Taiwan. Furthermore, a few countries for which our linear model returns a negative SIDI in the year 2020 have been removed:

Central African Republic, Democratic Republic of the Congo, Eritrea, Guinea, Guinea-Bissau, Liberia, Sudan, Somalia, Chad and Togo. In total, projections of the SIDI and associated calories were calculated for 130 countries.

5.4.4 Share in rain-fed agriculture

The share of rainfed agriculture in the total calorie production was found to have the highest explanatory power over variations in the SIDI across countries. It is defined as:

$$Share\ rainfed = \frac{C_{rain}}{(C_{irr} - C_{irr}^{u}) + C_{rain}}$$

Where C_{rain} denotes the current (2000) calories produced with rain-fed agriculture. C_{rain} and C_{irr}^{u} are projected to stay constant in a YGC scenario, as we do not account for the impacts of future climate changes (please see Figure D.3 in Annex D). However, since Share_rainfed evolves along with the number of calories produced via sustainable irrigation, we calculate it analytically for each time step (every 5 years, see SM for more information).

5.4.5 Calories

To assess the calorie production through sustainable irrigation over time, we multiply SIDI estimates at a time t with the calories produced via sustainable irrigation in a YGC-scenario, following Equation 6.

$$Calories(t) = SIDI(t) * YGC_{irr}$$

Calculation of additional people fed in a given scenario and for a specific year requires an estimation of caloric intake per person. Rosa et al (2018) calculated the daily calorie requirements equivalent to a diet with 20% animal products by assessing the caloric and protein contents of each crop. After accounting for conversion efficiency, they arrived at an estimate of 3343 vegetal kcal required per capita and per day. For each SSP, we calculate the sum of all calories produced in 2020, 2050 and 2100 in all countries using Equation 7 to arrive at global values. To assess the additional people fed, we subtract the number of people fed in 2020 from the corresponding 2050 and 2100 estimates. The average calories were then averaged over the World Bank regions. Further, the percentage increase in sustainable calorie production compared to 2020 and up until 2100 was calculated as:

$$Percentage\ increase = 100 * \frac{calories_{projected}(t) - calories_{2020}}{calories_{2020}}$$

The total amount of people fed at YGC globally (~4 billion) was quantified from the dataset by Rosa et al (2018) by summing the maximum calories produced (for the same countries as in this analysis), dividing the calories by 365 days (to arrive at the per day estimate) and further dividing the result by 3343 vegetal kcal to arrive at the total people that can be fed at YGC. The same method was applied to quantifying the total amount of people fed via sustainable irrigation at the end of the century for the different SSPs (~2 billion).

5.5 Projecting sustainable irrigation deployment

The coefficient estimates from the regression model are applied on the governance projections (Andrijevic, Crespo Cuaresma, et al. 2020a) from the SSPs, which allows for future projections of the SIDI over the 21st century for each of these five scenarios, also taking into account the progression of the share in rain-fed agriculture at every time step as irrigation is deployed (see Methods). In Figure 5.3a the global and regional development of the SIDI is displayed, with projections starting in 2020 and ending in 2100. The red dots in Figure 5.3a display the SIDI that was quantified using data (Rosa, Rulli, et al. 2018) from 2000 and serve as reference points. Figure 5.3b shows the regional differences for a Middle of the Road scenario (SSP2).

The projections of the SIDI alongside the five SSPs display large heterogeneities between regions and scenarios. Globally and regionally Figure 5.3a, SSP5 and SSP1 are the most optimistic scenarios, which is consistent with the scenario storylines, as governance reaches the highest levels in these two scenarios. SSP3, also in line with

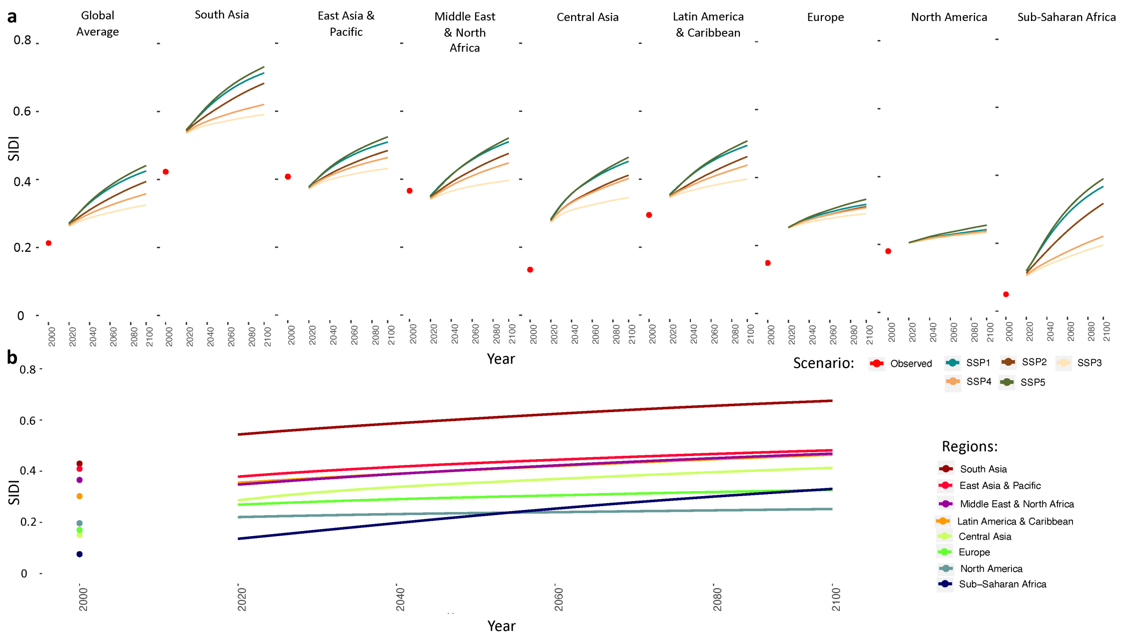


Figure 5.3: Projections of the Sustainable Irrigation Deployment Index. (a) Trajectories are shown for global and regional and for the different SSP-scenarios. (b) Regional projections of the SIDI for Middle of the Road scenario (SSP2). The data for 2000 (observed) is from Rosa et al. (2018) and the projections are shown from 2020 until 2100. The regional projections are displayed for the World Bank regions31 (delineation of the regions can be seen in Fig. 3).

the storylines, is the most pessimistic scenario, displaying the smallest improvements for the index both globally and regionally. The global average SIDI for the year 2000 is estimated at 0.23 Figure 5.3a. This indicates that only 23% of the global sustainable irrigation potential was being used at the beginning of the century. The global SIDI is projected to improve from 0.23 to 0.43 in a Sustainability scenario (SSP1) – which implies that globally 43% of the sustainable irrigation potential could be utilized by the end of the century. In contrast, in a Regional Rivalry scenario (SSP3), the SIDI would only improve to 0.34. In this scenario, we would only use 34% of the sustainable irrigation potential globally by the end of the century.

Regional results for the baseline SIDI vary largely (between 0.5 and 0.4) in year 2000 (Figure 5.3b). South Asia has the highest SIDI in 2000, followed by East Asia & Pacific – both displaying results above 0.4. This indicates that, compared to other regions, these two are currently using a high fraction of their sustainable irrigation potential (around 40%) and therefore the ability of their agricultural sector to buffer precipitation variations via irrigation endows them with a relatively high adaptive capacity (Figure 5.3a). Countries in this region, such as India or Pakistan, are known for their strong dependence on the agricultural sector and have already implemented large-scale irrigation systems in the past (Anik et al. 2017), although this has led some of them to currently rely on unsustainable exploitation of water resources (Rosa, Rulli, et al. 2018). South Asia is the region closest to narrowing the yield gap by the end of the century, reaching an index of 0.70 in a Sustainability scenario (SSP1). In SSP3, South Asia will reach a SIDI of 0.58 in 2100.

In contrast, the region with the smallest SIDI in year 2000 is Sub-Saharan Africa (0.05), which indicates that the region is currently using very little of its sustainable irrigation potential. This is because most countries in the region do not yet have the possibility to access water management technologies and benefit from irrigation (i.e., face economic water scarcity), even though irrigation has long been emphasized as a solution to intensify agricultural production, support rural economic development and enhance resilience to climate variability and change (Lefore et al. 2019; Higginbottom et al. 2021). This also relates to the low levels of governance (e.g. ineffective national bureaucracies), which has hindered large-scale irrigation projects in Sub-Saharan Africa in the past (Higginbottom et al. 2021). The projections of the SIDI emphasize the vast potential for improvement in the region. In a Sustainability scenario, Sub-Saharan Africa could reach a SIDI of 0.38 by 2100, a $> 600\%$ improvement compared to 2000 levels. In contrast, in SSP3 the SIDI of the region would not go above 0.21. As can be seen in Figure 5.3b, Sub-Saharan Africa will reach the same SIDI levels as Europe by the end of the century in a Middle of the Road-scenario (SSP2).

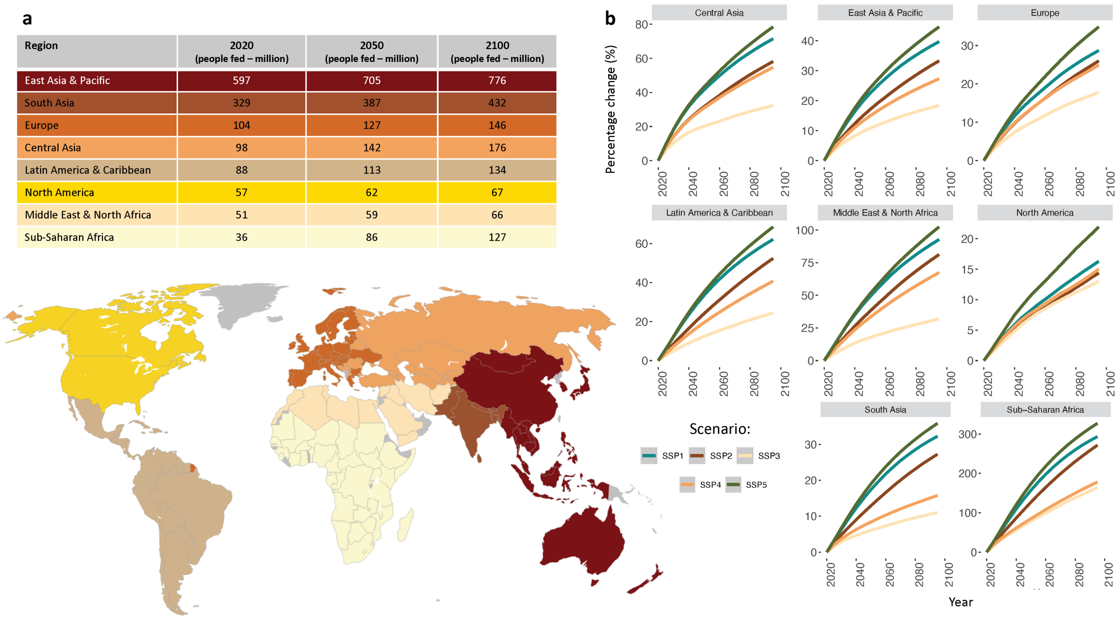
The remaining regions (Central Asia, Europe, Latin America & Caribbean, Middle East & North Africa and North America) reached indices comparable to the global average (between 0.1 and 0.3) in year 2000. Regions such as Europe and North America are, despite their level of development, not yet using a lot of their sustainable irrigation potential and reach an index around 0.2. This is because most countries within that region rely heavily on rain-fed agriculture for their caloric production but have a reduced dependency on irrigated agriculture (under current climatic conditions). Moreover, Europe and North America already feature high levels of governance in the baseline period, which diminishes their sustainable irrigation expansion in our analysis.

5.6 People fed via sustainable irrigation

Future increase in sustainable irrigation as proxied by the SIDI and projected alongside the SSPs can be translated into potential calorie production and people fed. Figure 5.4a shows the total people fed via sustainable irrigation in 2020, 2050 and 2100 within a region. The number of people fed is displayed for a Sustainability scenario (results for other SSPs can be deduced from Tab. S3). Figure 5.4b shows the percentage increase from 2020 throughout the 21st century for the different SSP scenarios. Governance estimates are only available until 2095, therefore our projections also end in this year. However, we assume the same level of the SIDI and calories produced in 2095 and 2100, to match the population estimates.

According to our model estimates, the region East Asia & Pacific is currently able to produce the highest level of calories via sustainable irrigation in 2020 and feeds a total of 597 million people. South Asia is the region with the second highest calorie production, with a total of 329 million people being fed via sustainable irrigation in the same year. The lowest calorie production and number of people fed through sustainable irrigation is apparent for Sub-Saharan Africa and Middle East & North Africa (36 million and 51 million, respectively) (Figure 5.4).

The analysis shows that the regions in which a lower amount of people are fed via sustainable irrigation in 2020 are able to make the greatest improvements by 2100 in that regard. Sub-Saharan Africa, for example, will experience the highest percentage increase in people fed via sustainable irrigation, by more than 250% until 2100 (compared to 2020) in a Sustainability scenario. This would increase the total amount of people being fed via sustainable irrigation from 36 million people in 2020 to 127 million people by the end of the century (Figure 5.4).



Region	2020 (people fed – million)	2050 (people fed – million)	2100 (people fed – million)
East Asia & Pacific	597	705	776
South Asia	329	387	432
Europe	104	127	146
Central Asia	98	142	176
Latin America & Caribbean	88	113	134
North America	57	62	67
Middle East & North Africa	51	59	66
Sub-Saharan Africa	36	86	127

Figure 5.4: People fed via sustainable irrigation in 2020, 2050 and 2100. (a) Total amount of people fed per region in 2020, 2050 and 2100 via sustainable irrigation for the World Bank regions in SSP1 (people fed reported in million per year). (b) Percentage change in people fed via sustainable irrigation (per country) is also shown for the World Bank regions and the five SSP scenarios from 2020 until 2100. Results for the other SSPs can be found in Annex D Table 3.

In contrast, East Asia & Pacific, the region with the highest amount of people fed via sustainable irrigation in 2020, will improve by around 30% until 2100 in a Sustainability scenario (SSP1). That percentage improvement would still increase the amount of people fed from 597 million people in 2020 to 776 million people by the end of the century in SSP1. This is the highest regional average in our analysis. Differences between the socioeconomic scenarios are less pronounced in regions with smaller relative improvement (e.g., a 3% difference between SSP1 and SSP3 in North America as opposed to 140% difference in Sub-Saharan Africa) (Figure 5.4.

Globally, we find that in SSP1, sustainable irrigation could feed a total of 1.93 billion people by the end of the century (Table 5.1). When relating this to the estimated population increase, we project that 28% of the global population could be fed via sustainably irrigated calories produced. In contrast, only 1.54 billion people could be fed via sustainable irrigation by the end of the century in a SSP3 scenario – which could feed 12% of the global population. The analysis shows that SSP1 and

Scenario	2020 (billion people)	2050 (billion people)	2100 (billion people)	Population in 2100 (billion people)	% fed in 2100
SSP1	1.36	1.68	1.93	6.88	28%
SSP2	1.34	1.58	1.80	9.00	20%
SSP3	1.32	1.46	1.54	12.6	12%
SSP4	1.33	1.54	1.71	9.27	18%
SSP5	1.35	1.70	1.98	7.36	27%

Table 5.1: Total people fed globally with sustainable irrigation in 2020, 2050 and 2100, population projections and the fraction of people fed via sustainable irrigation per SSPP. Total people fed was quantified assuming a calorie intake of 3343 kcal per capita per day (Rosa et al. 2018). Population projections are for each SSP in the year 2100 (KC and Lutz 2017). People fed are displayed in billion per year.

SSP5 will have the best chances at meeting projected global food demands, whereas SSP3 and SSP4 will face the highest challenges in reaching that objective (Table 5.1).

5.7 Fraction of yield gap closure level

In a yield gap closure scenario and using estimates from (Rosa, Rulli, et al. 2018), a total of 4 billion people could potentially be fed via sustainable irrigation in the absence of socioeconomic constraints (See Table D.1 in Appendix D). However, our results show that socioeconomic factors are most probable to substantially constrain this potential. Even by the end of the century, in the most optimistic scenario (SSP1), only about half of the theoretically possible potential would be realized (about 2 billion people). 1.4 billion people are fed with sustainable irrigation in 2000, curtailing the future additional potential even further (compare Table 5.1). This underlines a growing need to incorporate socioeconomic projections into analyses of future food security (Beltran-Peña et al. 2020).

Figure 5.5a compares yield gap closure potential under SSP1 with irrigation biophysical potentials. By 2100 under SSP1, South Asia will be able to use 70% of the irrigation yield gap closure potential, followed by the Middle East & North Africa (54%) and Latin America & Caribbean (49%). By contrast, panel B displays the amount of people per region that could be fed via sustainable irrigation by the end

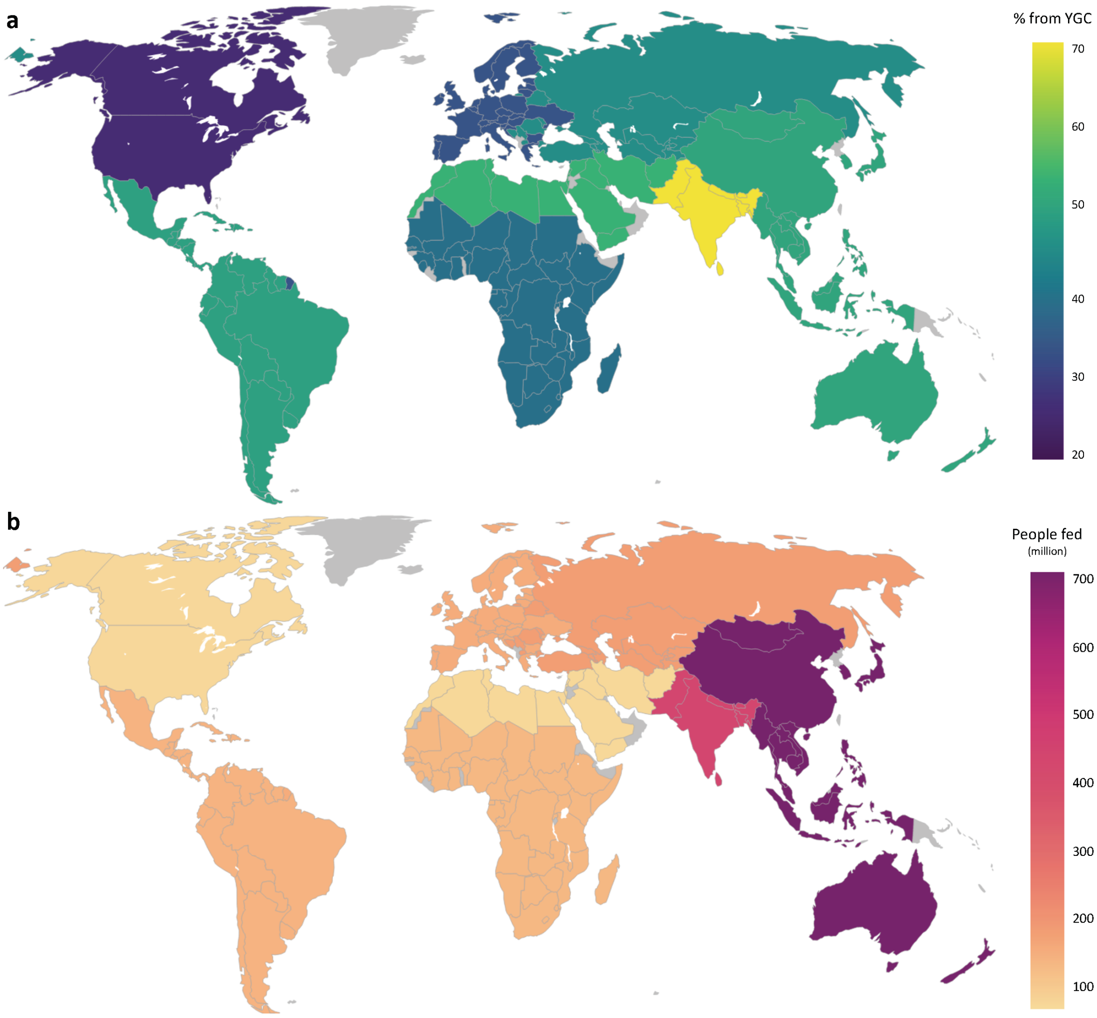


Figure 5.5: Projected sustainable irrigation potential used in a Sustainability scenario (SSP1) compared to a YGC scenario and people fed by the end of the century. (a) Percentage difference between projected sustainable irrigation calories produced in 2100 for a Sustainability scenario (SSP1) and sustainable irrigation calories produced in a YGC-scenario from Rosa et al. (2018). (b) Total amount of people fed per region (reported in million per year) via sustainable irrigation in 2100 for SSP1.

of the century for SSP1. While East Asia & Pacific is the country with the highest number of people fed (776 million), we find South Asia (432 million) and Central Asia (146 million people) to be countries with high sustainably irrigated calorie production and thus population fed, by the end of the century. Sub-Saharan Africa, which was the region with the lowest people fed in 2020, is projected to feed more people by the end of the century (127 million) than North America (67 million) and Middle East & North Africa (66 million). This shows, for example, that in Europe the number of people fed via sustainable irrigation is comparably high (146 million), while their yield gap remains substantial (33% from YGC). By the end of the century, none of the regions will close the yield gap in neither of the scenarios. Nevertheless, substantial increases in people fed via sustainable irrigation can be recorded.

5.8 Irrigation in the context of climate change

Consistently with the SSP framework that by design does not account for impacts of future climate change, we also do not account for those in our projections (O'Neill, Kriegler, et al. 2017). Both the SIDI and future estimates of sustainable irrigation potential were thus derived using present-day crop water requirements and surface water availability quantities. However, future calorie production and the sustainable irrigation expansion potential will be impacted by climate change through its alteration of precipitation amount and timing, the occurrence of extreme events (Tabari 2020), as well as changing soil moisture and crop water requirements (Rosa, Chiarelli, Rulli, et al. 2020). Changes in water availability and demand and higher exposure to heat extremes are, for example, projected to negatively impact local agricultural production and reduce potential benefits of CO2 fertilization in the Mediterranean, Central America, the Caribbean, South Africa and Australia (Schleussner, Lissner, et al. 2016; Byers et al. 2018).

5.9 Implications for climate adaptation

Irrigation is one of the most prominently discussed adaptation measures to climate change (Rosa, Chiarelli, Rulli, et al. 2020), however its negative consequences, including environmental flows impairment and depletion of freshwater stocks, are not always acknowledged. Understanding the potential for sustainable expansion of irrigation is essential, as climate change adaptation will likely drive a substantial expansion of this technology. In addition, the multiple facets of socioeconomic development that determine a countries' capacity to tap into existing sustainable irrigation potentials remains largely ignored in this context. Our scenarios do not explicitly represent the impacts of climate change that would provide a perspective on the need for irrigation expansion as an adaptation measure. But they illustrate what socioeconomic constraints may exist to its successful implementation, as for many world regions irrigation expansion would already be a highly effective adaptation measure under current climate conditions. They highlight that even existing and well-established technologies such as irrigation may be limited in their availability to alleviate impacts at higher levels of warming. It is important to highlight that our scenarios do not provide an upper limit of what could be possible in terms of irrigation deployment as a climate adaptation measure, but that other factors, which we were not able to include in our analysis, could further enable the implementation of sustainable irrigation. Overcoming socioeconomic constraints to improve adaptation deployment under climate change is a distinct possibility, and in some cases might be a necessity to prevent substantial reductions in agricultural productivity (Rosa, Chiarelli, Rulli, et al. 2020). Our findings highlight that this might be all but easy given the observed evidence of socioeconomic factors limiting the effectiveness of irrigation deployment (Higginbottom et al. 2021).

5.10 Discussion

By introducing the Sustainable Irrigation Deployment Index we assess how socioeconomic conditions are related to the current level of sustainable irrigation with respect to its potential under a yield gap closure scenario. In our analysis, a governance indicator – defined as the institutional capacity of countries – emerges as a socioeconomic factor that best explains the current level of sustainable irrigation deployment. Our findings on the importance of governance and institutions as key conditions for the successful deployment of such adaptation options are in line with other findings on indices reflecting adaptive capacity (Higginbottom et al. 2021). The two identified predictors, namely the level of governance and the share of rainfed agriculture, are able to explain more than 70% in the current variations in used sustainable irrigation potential across the globe. By comprehending which factors currently hinder or enable sustainable irrigation, we are able to project the evolution of sustainable irrigation deployment throughout the 21st century alongside the socioeconomic development of countries.

Socioeconomic constraints that currently limit sustainable irrigation expansion are particularly prominent in regions such as Sub-Saharan Africa, where less than 1% of the sustainable irrigation potential is currently being used. Due to the currently low levels of socioeconomic development, it will and has been more challenging to introduce new farming approaches, such as retaining rainwater for irrigation. This is in line with findings from Holman et al. (2019), who report that the implementation of irrigation systems, despite large-scale investments in its infrastructure, where hindered by centralized bureaucracies, lacking technical expertise and political incentives (Higginbottom et al. 2021). However, in regions where most of the population growth is expected to occur in the coming decades, it will be crucial to reach much higher levels of adaptive capacity in the agricultural sector, to counteract already existing hunger and malnutrition. For example, in the Sahel region, where less than 4% of cropland is currently equipped with any kind of irrigation infrastructure and where population growth is already outstripping food supply, population is expected to more than double to 450 million by 2050 (Graves et al. 2019). International and local efforts need to focus on increasing adaptive capacity in these regions, as well as specific support for irrigation deployment in the agricultural sector, to support the well-being of hundreds of millions of people.

The findings presented in this study can be useful for impact or crop models that assess potential future crop yields. While sustainable freshwater constraints are increasingly considered in such modelling efforts (Wang et al. 2021), socioeconomic considerations limiting irrigation deployment are so far not consistently implemented. Our projections also provide important entry-points to include information on the future climate resilience and adaptive capacity for policy-making in Integrated Assessment Models (IAMs). We report a substantial scenario dependence of future sustainable irrigation expansion which underscores the need to incorporate socioeconomic variables into projections of future agricultural developments. This study provides a starting point for the analysis of other adaptation options, such as crop migration (Sloat et al. 2020), or for other sectors in which adaptation will be determining for climate resilience (e.g., reservoirs planning for irrigation). Assessing the future adaptive capacity of countries and including this information in impact assessments will be of key importance to assess pathways to climate resilience. The capacity of countries to ensure food security in the context of rapidly changing biophysical conditions will be one of the major determinants for the next century (Myers et al. 2017). In summary, our results show that by improving the socioeconomic conditions (e.g., governance) of countries, we will move closer to reaching the Sustainable Development Goal (SDG) of zero hunger and other highly relevant and interrelated SDGs, highlighting their interconnectedness and the importance of a holistic sustainability agenda.

Acknowledgments

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Data availability

Data and code are available at Github (`https://github.com/nicolenicolen/Sustainable_irrigation_2021`)

6 Conclusion

6.1 Synthesis

The extent to which “weather turns into disasters” (Otto et al. 2020) is not only contingent on the physical properties of climate change hazards but crucially depends on socio-economic factors that contribute to exposure and vulnerability to those hazards (Byers et al. 2018; Schleussner, Deryng, et al. 2018). Current manifestations and future projections of climate change have been pointing to the need for adaptation alongside the urgent and stringent mitigation, most notably in areas of the world that are at the frontline of climate change.

With the need for it apparent in many parts of the world, adaptation science has been rapidly advancing over the past two decades. The portfolio of options has been growing, together with the understanding of the potential of adaptation to reduce climate risks. However, scenarios that are used to answer the “what-if” questions on strategies to deal with climate change are not yet advanced in analyzing various adaptation-related challenges and their temporal trajectories. Modeling tools that assess policy options and how they might affect climate change outcomes do not yet incorporate quantified adaptive capacity indicators that would help compare the interlinkages between socio-economics and climate hazards. Instead, climate impacts tend to be estimated with stylized adaptation scenarios: no adaptation or optimal (or maximum) adaptation. For improved predictive capabilities of models, a more nuanced representation of adaptation and its possible pathways is needed.

It is unclear, at least from a global modeling perspective, under which conditions would adaptation be pursued optimally, and under which it would be inadequate. In other words, quantitative assessments do not yet account for adaptive capacity that depends on economic, financial, institutional and other barriers, which might render the “optimal” adaptation unattainable. While many of the barriers can be overcome as part of broader socio-economic dynamics, the pace at which this can happen remains elusive. Understanding of the temporal evolution of barriers, or whether and how they can be overcome, is crucial for anticipating the adaptive capacity of a household, community or country to cope with climate change.

Expectations of adaptation that are not embedded within the broader socio-economic context may lead to inaccurate climate change impacts, as well as their human and monetary damages, not least because many areas where adaptation is most pressing also face major development challenges. Understanding the temporal trajectories, and the soft and hard limits of improvements in adaptive capacity would add an additional layer to the identification of hotspots of high climate risks where hazards, exposure and vulnerability overlap. Insights into adaptive capacity are also relevant in the context of loss and damage, which will require policy responses designed to support countries exposed to climate hazards with limited capacity to adapt.

With the aim to provide high-level information that global assessments can incorporate, the established conceptual connections and methodological advancements presented in this thesis close an important gap in the current literature. The thesis develops a flexible toolkit to account for adaptive capacity in scenarios of future socio-economic development, with the aim to advance the representation of adaptation in quantitative climate change research. The chapters presented here connect the largest synthesis of climate science and a set of global scenarios commonly used in climate change research to provide a comprehensive view on economic, financial, educational and other socio-economic dimensions important for adaptive capacity in the context of SSP scenarios. This integration enables an assessment of the future pathways of adaptive capacity. Trajectories of adaptive capacity are a major step towards understanding adaptation challenges, which are at the core of the SSP scenarios. Adaptive capacity can be regarded both in the context of possible policy options and exploring uncertainty surrounding future climate impacts. The toolkit is intended for future application in climate impact models and for assisting the efforts to incorporate climate impacts in the scenario framework and more broadly in the Integrated Assessment Models as the key tools used in the science-policy interface.

6.1.1 Extensions of the SSP scenarios

Extensions of the SSP scenario set with indicators of governance and gender inequality shown in Chapters 2 and 3 help cover all categories of adaptation barriers identified in the AR5. As some of the most pertinent adaptation barriers, timelines of attaining better governance and overcoming gender inequality are key considerations in understanding the temporal evolution of adaptive capacity.

Governance is, together with financial capacity and access to information, an adaptation barrier present across all regions and all but two sectors. Though it was featured qualitatively in the SSPs, Chapter 2 presents the first quantification of governance to date. Strengthening governance (or its dimensions such as control of corruption, political stability and quality of institutions) will be crucial for increased adaptive capacity. Processes necessary for the implementation of adaptation include prioritizing policies, mobilizing resources, coordination of efforts and decision-making, all of which hinge on the governance level. Additionally, poor governance can make other capacities (e.g. finance) less effective, thereby making governance-related improvements a crucial complementary effort in enhancing other dimensions of adaptive capacity. This chapter shows vast between-country inequality in the present-day state of governance and scenario-dependent trajectories of future development. For many currently developed countries, on the one hand, there is only a minor scenario difference because they already exhibit high levels of governance, and scenarios do not incorporate any deterioration. On the other hand, for developing countries, the difference in the level of governance between the best and worst-case scenarios can be up to threefold. Finally, the results suggest that countries that have suffered from conflicts and political instability over the observational period of the last three decades could - even in scenarios of fast socio-economic progress - take another three decades or longer to reach governance levels that countries from the Organization for Economic Cooperation and Development (OECD) exhibit today.

Gender inequality – the focus of Chapter 3 – as a socio-cultural barrier is also one of the most pertinent barriers present in all but two sectors and one region. Gender inequality affects primarily women, through various channels including unequal access to various types of adaptation-relevant resources that put them at a disadvantage. However, gender inequality as a component of adaptive capacity is relevant for all actors involved in adaptation. In simplest terms, if women as half of a given population are disadvantaged in the capacity to adapt to climate change, this spills over to the population as a whole. Gender inequality is featured qualitatively in the SSP storylines and is also quantitatively present by indicating the gender gap in mean years of schooling (KC and Lutz 2017). Chapter 3 expands this quantification with a more comprehensive indicator which also captures inequalities in health and participation in political and economic life. The latest observed values of the Gender Inequality Index (GII) used throughout this chapter depict a stark North-South divide. However, in progressive socio-economic development scenarios, almost a total global convergence can occur by mid-century. Compared to indicators of governance, gender inequality (measured by the GII indicator) could be improved upon faster across the world. In the paper, we argue that improving upon the GII indicator, however, does not automatically mean that gender equality is universally achieved, but rather that improvements in "basic" inequalities (such as health care, education and employment) are possible already in the near term with sufficient investments and international cooperation.

The usefulness of indicators of governance, gender inequality and other SSP components is not limited to climate change research. Governance and gender equality are cornerstones of two Sustainable Development Goals (SDGs), number 16 and 5 (UN General Assembly 2015). The analyses shown in Chapters 2 and 3 can be useful for exploring the SDGs to the extent that they show the possible trajectories of development and global inequalities in the pace of improvement in different scenarios. These trajectories can help identify the socio-economic processes that happen in parallel with progress in the given indicator (e.g., GDP per capita growth, expansion of tertiary education, reduction of the gender gap in education).

6.1.2 Sectoral applications of adaptive capacity assessments

The two sectoral applications in Chapters 4 and 5 demonstrate the use of the SSP framework to assess adaptive capacity. Both chapters use an econometric approach to identify dimensions of adaptive capacity related to the use of air conditioning as an adaptation option against heat (Ch. 4) and deployment of irrigation as an adaptation strategy in the agricultural sector (Ch. 5).

In the human health sector of climate impacts, Chapter 4 advances the current methodological approach to modeling air conditioning ownership by expressing it as a function of income, urbanization and income inequality. SSP projections of those three dimensions of adaptive capacity allow for deriving future AC ownership rates in different socio-economic development scenarios. By coupling future AC rates with future population projections, we estimate the cooling gap, which expresses the difference between the population exposed to heat stress – as one of the universal manifestations of climate change – and the population with access to air conditioning. Our estimates show that, particularly for areas of fast population growth, large shares of the population already are and will continue to be exposed to heat stress, with the cooling gap varying between 2 billion people globally in SSP1 to 5.2 billion in SSP5. Scenario-dependent adaptation potential (illustrated by AC ownership) is now available for use in estimates of overall climate impacts of heat stress by accounting for the extent to which heat stress can be reduced with adaptation.

Chapter 5 focuses on irrigation as an adaptation option in the agriculture sector. The Chapter's centerpiece is the so-called Sustainable Irrigation Deployment

Index (SIDI), used to express the gap between the maximum potential crop yield and the actual crop yield on the country level. The extent to which this gap can be closed with irrigation depends on the socio-economic ability to deploy sustainable irrigation. The analysis of this Chapter finds that sustainable irrigation is related to the countries' levels of governance (measured by the governance indicator introduced in Chapter 2). The relationship between SIDI and governance allows for projections of the future yield gap, which vary widely between regions and scenarios. The governance barrier for irrigation is particularly relevant for Sub-Saharan Africa, where governance might take decades to improve, while almost no sustainable irrigation is currently taking place and only slow improvements are projected without additional efforts to improve institutional conditions. Low levels of governance are can render financial resources for irrigation ineffective, which stresses the need for holistic assessments of adaptation barriers. Projections presented in this Chapter are the first step to including information on the future adaptive capacity in the agriculture sector, such as in crop models that assess potential future crop yields, where socio-economic considerations of irrigation deployment have not been implemented.

6.2 Limitations

6.2.1 Conceptual limitations of adaptive capacity

Some of the recent research distinguishes between the adaptive capacity anchored in Sen's capability approach (Sen 1999) (the conceptualization of adaptive capacity used in this thesis) and the approach that captures not only the latent capacity but also the mobilizing mechanisms which turn the capacity to adapt into an actual adaptation implementation (Pelling and High 2005). This distinction is motivated by instances in which areas with high adaptive capacity (based on the dimensions such as financial and human capital) do not necessarily reflect high adaptation implementation (Morteux and Barnett 2017; Gawith et al. 2020) and vice versa. However, such outliers do not invalidate this approach on the global scale presented here, where the between-country dynamics robustly hold. However, only in hindsight and with longer time series and more harmonized methods to track adaptation it will be possible to better ascertain whether adaptation is taking place or not. Understanding the mechanisms that help translate adaptive capacity into adaptation implementation and identification of the hindrances is an important task for future research and will be useful for context-specific actions and local policy-making.

6.2.2 Contested adaptation options

Chapters 4 and 5 use air conditioning and irrigation, which are controversial adaptation options, primarily because of their emissions footprint, in the case of air conditioning, or impact on water availability, in the case of irrigation. They are, however, relatively straightforward to measure and quantify, which makes them a useful starting point to showcase applications of the adaptive capacity toolkit. Our results highlight that existing and well-established technologies (even if contested) may be limited in their availability to tamper the impacts of climate change, particularly at higher levels of warming. Future research should advance the analysis with alternative and additional adaptation options in these two sectors, as well as consider strategies that ensure that adaptation does not become maladaptation (Barnett and O'Neill 2010).

Additionally, adaptation options can involve more complicated interactions between different actors and sectors (Patt et al. 2010). Some adaptation options might not be quantifiable (e.g. cultural traditions), and rather be explored through qualitative scientific methods or mixed methods approaches. Limitations to quantification need to be recognized and not necessarily forced into a modeling environment.

6.2.3 Limitations of the global approach

All analyses throughout this thesis are done using country-level data and relied on exploiting the between-country variation on the global level. The internal dynamics that shape the SSP's trajectories are also global, a setup that is appropriate for the types of models that operate on large geographical scales. However, global representation has limitations for the exact implications relevant for specific local contexts. These limitations could be overcome with downscaling efforts and regional extensions of models which can capture both the climatic and the socio-economic conditions on a more refined resolution (Wouterse et al. in review; Chepkoech et al. 2020; Stöber et al. 2017). Combining the advantages of a global analytical model dynamics with qualitative context-specific assessment of future trajectories of socio-economic components can improve the local applicability of projections. The adaptive capacity toolkit presented here could be used with sub-national data and scenario storylines adjusted to represent the local conditions better (Smits et al. 2021). Additionally, the bottom-up approaches that will assess scenarios of adaptive capacity on the household level can be another promising avenue of research that will help policy-makers identify areas of priority in the local context.

6.2.4 Limitations of the SSP scenarios

Scenarios are sometimes misconstrued as predictions of the future. Rather than predicting, they are meant to help researchers and policy-makers explore the uncertainty space and provide a consistent research platform for "what-if" types of exercises. Of course, they are neither definite nor do they span the entire set of possibilities of what might happen in the future.

The SSP scenarios that this thesis builds on suffer from their shortcomings that could be addressed in the future but need to be kept in mind when using and interpreting the adaptive capacity indicators develop here. Firstly, they do not account for shocks such as economic crises or the pandemic, which could set back improvements in socio-economic conditions made in the past. The absence of such disruptions makes the scenarios inherently optimistic, where even the worst-case scenario looks more like stagnation than deterioration. As shown in Chapter 3 on governance projections, the scenario optimism cannot incorporate observed dynamics such as the rapid decline in the governance indicator in Syria in the aftermath of the war. The dynamics behind these deteriorations are not straightforward to incorporate in deterministic modeling approaches underlying the

SSPs, representing a limitation of scenario frameworks in general. However, recent advances in forecasts of the probability of internal armed conflicts (Hegre, Buhaug, et al. 2016; Hegre, Nygård, et al. 2021) provide a way to consider projections of conflicts in future scenarios.

Secondly, in their current format, SSP scenarios represent long-term trajectories, i.e., until the end of the 21st century. The long time horizon is appropriate for considerations of slow-onset consequences of climate change and understanding the extent to which mitigation choices affect the climatic factors. As such, SSP scenarios are not necessarily useful for very near-term analyses of adaptation or socio-economic developments at large.

Finally, SSPs are meant to serve as baseline scenarios, that is, represent the world in the absence of climate policy and climate change. While useful for ensuring consistency across modeling groups, this is also the elephant in the room because climate impacts are already happening and will likely intensify and/or become more frequent. With increasingly robust evidence on future climate change hazards, it is unrealistic to, for example, expect perpetual economic growth in countries that are heavily reliant on agriculture or tourism, especially in the absence of adaptation considerations. Integration of such impacts will require a dynamic understanding of adaptive capacity, which is what the toolkit developed within this thesis is intended to help with.

6.3 Outlook

6.3.1 Future research

The toolkit for quantifying adaptive capacity presented in this thesis helps to account for heterogeneity in socio-economic conditions conducive for adaptation, in a way consistent with the state-of-the-art in climate change science. The methodological approach rests on the findings of the IPCC Working Group II reports on "Climate change impacts, adaptation and vulnerability", with the indicators of adaptive capacity embedded in the scenario set of Shared Socioeconomic Pathways. With a list of dimensions relevant for adaptive capacity continuously increasing with additional research, the portfolio of indicators presented here can be further enhanced with alternative and additional adaptation-relevant factors. Chapters 2 and 3 rely on existing multi-dimensional quantitative indicators of governance and gender inequality commonly used in the development arena, but they can by no means capture all relevant aspects of neither governance nor gender equality. The range of dimensions can also be updated with each new Assessment Report of the IPCC or other syntheses of evidence. Further extensions of the scenario set with alternative indicators would help validate the existing indicators and provide a more robust representation of a given dimension. A promising near term research agenda could be expanding the SSP set with indicators of technology (e.g., technology learning curves or technology adoption metrics for different adaptation options), costs of capital (related to the financing of adaptation investments), but also social conflicts and crises (including pandemics) which could cause major disruptions and decrease adaptive capacity.

Future research could use different approaches to deduce sector-specific components of adaptive capacity. Chapters 4 and 5 use simple econometric relationships to estimate the socio-economic factors conducive to the deployment of a given adaptation option. However, other approaches could, for example, assign weights based on findings of a literature review, meta-analyses, qualitative evidence, case studies, expert elicitation and other methods that can assess the relative importance of the different socio-economic factors. Alternative approaches would also add a robustness check to the results presented here.

The primary future use of the toolkit is intended for holistic estimates of climate change impacts. Projection exercises of the future cooling gap and yield gap in Chapters 4 and 5 indicate large regional inequalities in the level of adaptive capacity and the potential future uptake of adaptation. A next step would be for impact models to incorporate an indicator of adaptation that can be expected based on socio-economic conditions in estimates of climate-related heat stress risks for populations. Or, building on the results of Chapter 5, estimates of climate impacts on crops based can be adjusted for the level of irrigation can be expected given the socio-economic scenario. Importantly, the cooling gap and the yield gap used to demonstrate the application of adaptive capacity in the sectoral chapters are useful heuristic devices for identifying other gaps in adaptation beyond health and agriculture presented here. Future research based on different adaptation options across different sectors would give insights into the temporal pathways of closing those gaps.

Incorporating adaptive capacity as a component of complex IAMs requires an understanding of the individual models' requirements and identification of specific modules that could account for adaptation. However, models that already work with SSP scenarios will be well-equipped to do so. Concrete next steps would be to translate adaptive capacity pathways in the different SSP scenarios into model-specific parameters that estimate, for example, the economic impacts of climate change.

6.3.2 Relevance of adaptive capacity for loss and damage

Assessment of future development trajectories for overcoming barriers to adaptation can provide information about the plausible level of adaptation that societies might achieve at a certain point in time and thereby ascertain the projected loss and damage arising from climate hazards after the adaptation possibilities have been exceeded.

Analyses of future adaptive capacity can help identify barriers that can or cannot be overcome and thereby pose limits to adaptation, i.e., points beyond which a given system cannot be expected to counteract climate hazards with adaptation. Chapters 1 and 2 have shown even under scenarios of rapid and sustainable development, improvements of adaptive capacity in many low-income countries will take on average at least three decades. These timescales indicate that (temporal) limits to improvements in adaptive capacity exist in the near-term, but may also persist throughout the century, depending on which pathway of socio-economic development is followed. Slow improvements and low adaptive capacity increase the risks of climate change impacts, particularly in areas of lower socio-economic development. If adaptive capacity reaches limits to improvements, climate hazards would be more likely to outgrow the possibilities to adapt, thereby increasing risks and severity of impacts. Loss and damage for areas such as Sub-Saharan Africa or Small Island Developing States emerge even from model estimates which rely on optimal adaptation, which suggests that loss and damage would increase if the ability to adapt is not sufficient to do so in an optimal way (Markandya and González-Eguino 2019).

A recent case study on loss and damage from Bangladesh (Bhowmik et al. 2021) identifies a lack of capacities such as access to technology, information and income-generating activities to relate to adaptation limits. Inability to adapt results in residual damages that can be classified as loss and damage. Factors identified in the case study are consistent with the IPCC barriers to adaptation and the SSP framework. The advances made in this thesis with the temporal evolution of adaptive pathways could be a starting point to identify timescales of barriers to adaptation and the potential economic and non-economic loss and damage.

This thesis contributes towards a more advanced understanding of adaptation pathways, ultimately aiming to support the global efforts to prevent dangerous impacts of climate change while achieving sustainable development for all. Climate change risks will crucially depend on the level of vulnerability, which is a function of the capacity to adapt to climate change. Many areas of the world are experiencing intensifying climate impacts while trying to achieve multiple socio-economic development goals. The effects of anthropogenic climate change will be felt in these regions already in the near term (King, Black, et al. 2016), implying that adaptation actions are inevitable to reduce damages before the mitigation efforts show effect. With the need for adaptation apparent on both near and long-term time scales, it is important to understand the factors which act as barriers to building adaptive capacity and regard them in conjunction with broader development objectives. Tackling climate change in the context of sustainable development, as stipulated in Article 2 of the Paris Agreement, is one of the biggest challenges of our times. Adaptation will be crucial for overcoming that challenge, but it must not be taken for granted. Instead, substantial investments in various areas of socio-economic development will be needed to build adaptive capacities and support developing countries in efforts to minimize impacts and prevent loss and damage from climate change.

Appendices

A

Appendix for Chapter 2: Governance in socioeconomic pathways and its role for future adaptive capacity

Table A.1: Regression results

	Dependent variable:				
	Governance				
	FE	OLS	FE	FE	FE
	(1)	(2)	(3)	(4)	(5)
GDP per capita	0.044***	0.081***	0.043***	0.043***	0.048***
	(0.004)	(0.003)	(0.004)	(0.004)	(0.004)
Higher education	0.122**	0.576***			
	(0.052)	(0.041)			
Gender gap	−0.042***	−0.012***	−0.043***	−0.042***	−0.046***
	(0.005)	(0.003)	(0.005)	(0.005)	(0.005)
Primary education			−0.010		
			(0.039)		
Lower secondary education				−0.239***	
				(0.038)	
Upper secondary education					−0.206***
					(0.047)
Observations	2,754	2,754	2,754	2,754	2,754
R^2	0.978	0.613	0.978	0.979	0.978
Adjusted R^2	0.977	0.613	0.977	0.977	0.977
Note:			*p<0.1; **p<0.05; ***p<0.01		

Table A.2: Stepwise regression results (for the main specification)

	Dependent variable:		
	Governance		
	FE	FE	FE
	(1)	(2)	(3)
GDP per capita	0.055***	0.049***	0.044***
	(0.004)	(0.004)	(0.004)
Higher education		0.153***	0.122**
		(0.053)	(0.053)
Gender gap			−0.042**
			(0.017)
Observations	3,047	2,754	2,754
R^2	0.976	0.978	0.978
Adjusted R^2	0.975	0.976	0.977
Residual Std. Error	0.031 (df = 2842)	0.030 (df = 2560)	0.030 (df = 2559)
Note:		*p<0.1; **p<0.05; ***p<0.01	

Category	Percentile	Governance indicator range	ND-GAIN readiness range
Very good	>90th	>0.82	>0.67
Good	75th – 89th	0.66 – 0.82	0.52 – 0.66
Medium	50th – 74th	0.51 – 0.66	0.40 – 0.51
Weak	26th – 49th	0.39 – 0.50	0.30 – 0.39
Very weak	<25th	<0.38	<0.29

Table A.3: Categorization of the governance indicator and the ND-GAIN readiness indicator by percentiles and the respective ranges.

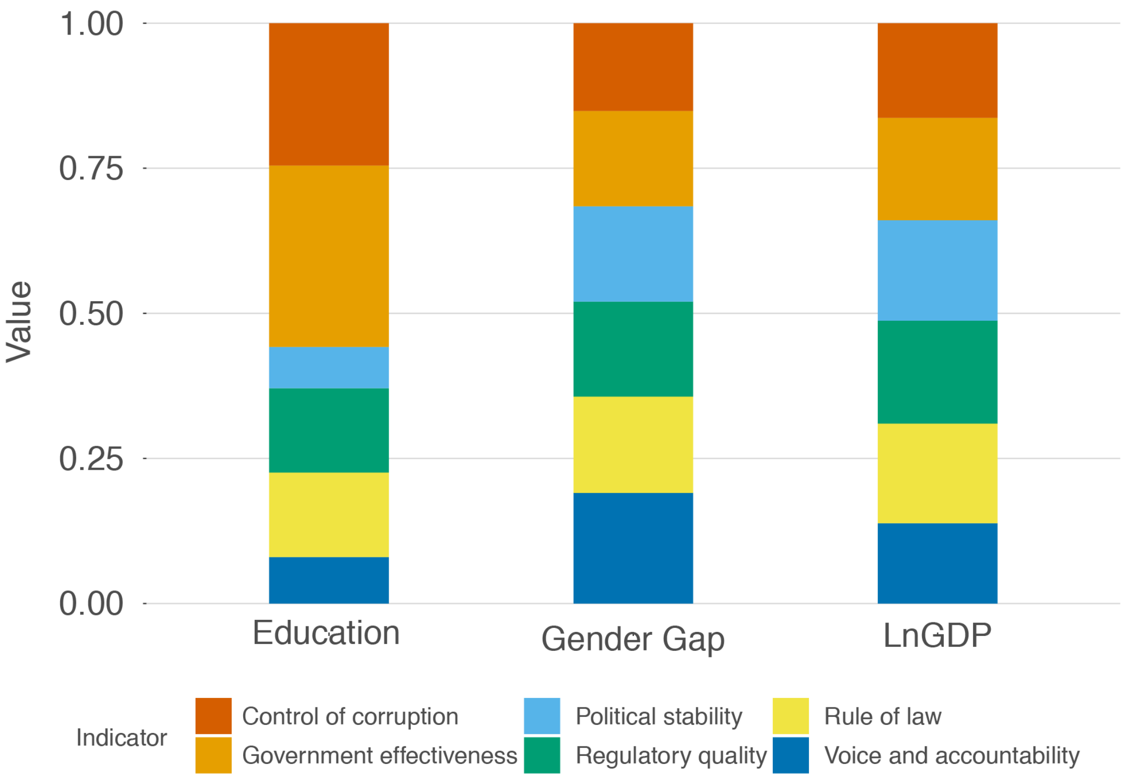

Figure A.1: Compositional analysis of regression coefficients. The bars show the proportion of each covariate's coefficient estimate that relates to each of the dimensions of the governance index. The distinct relationship is shown for post-secondary education having a comparatively larger effect on control of corruption and government effectiveness. Separate projections for these two components are shown on Figures 2-5.

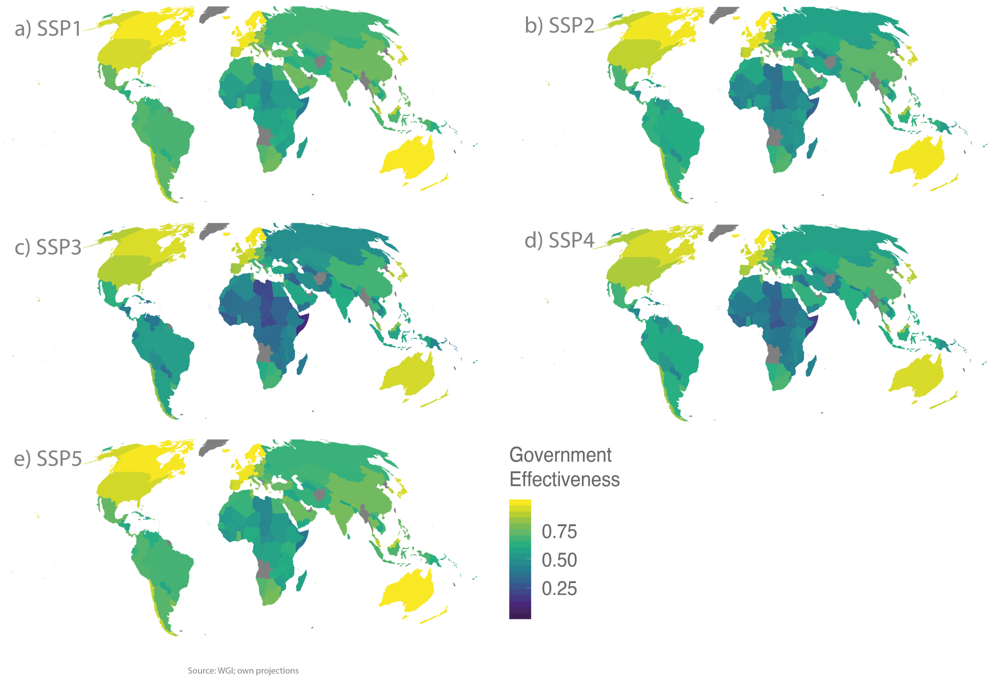

Figure A.2: Projections of the WGI government effectiveness component for 2050.

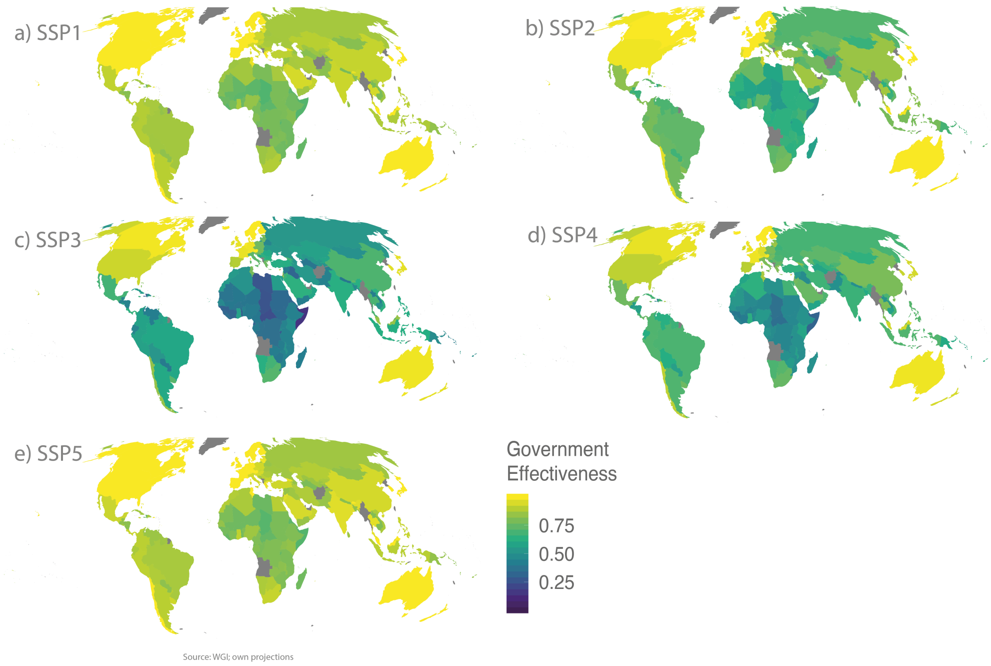

Figure A.3: Projections of the WGI government effectiveness component for 2100.

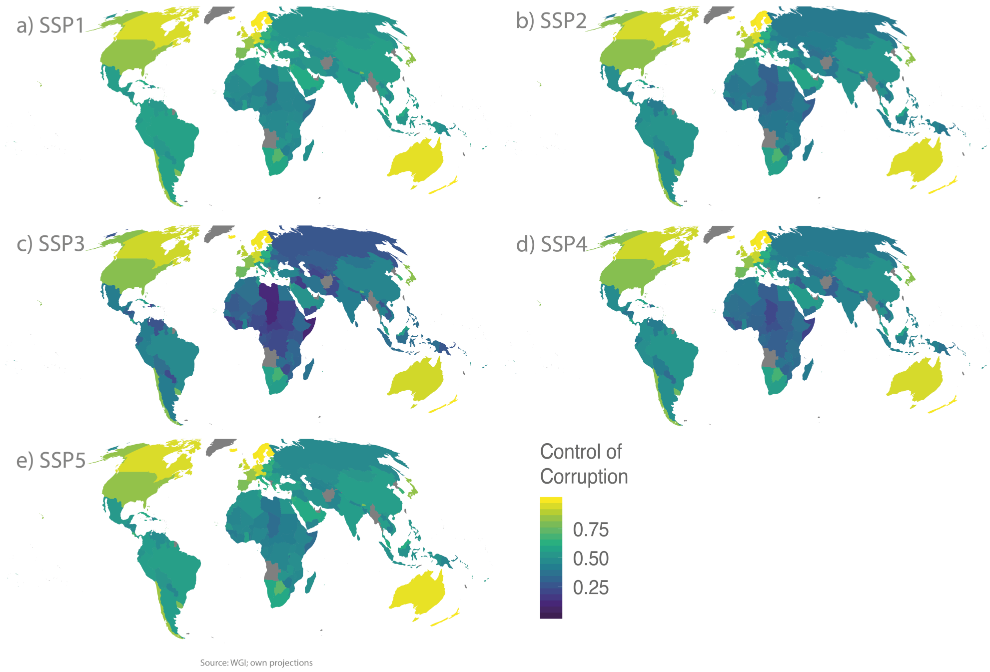

Figure A.4: Projections of the WGI control of corruption component for 2050.

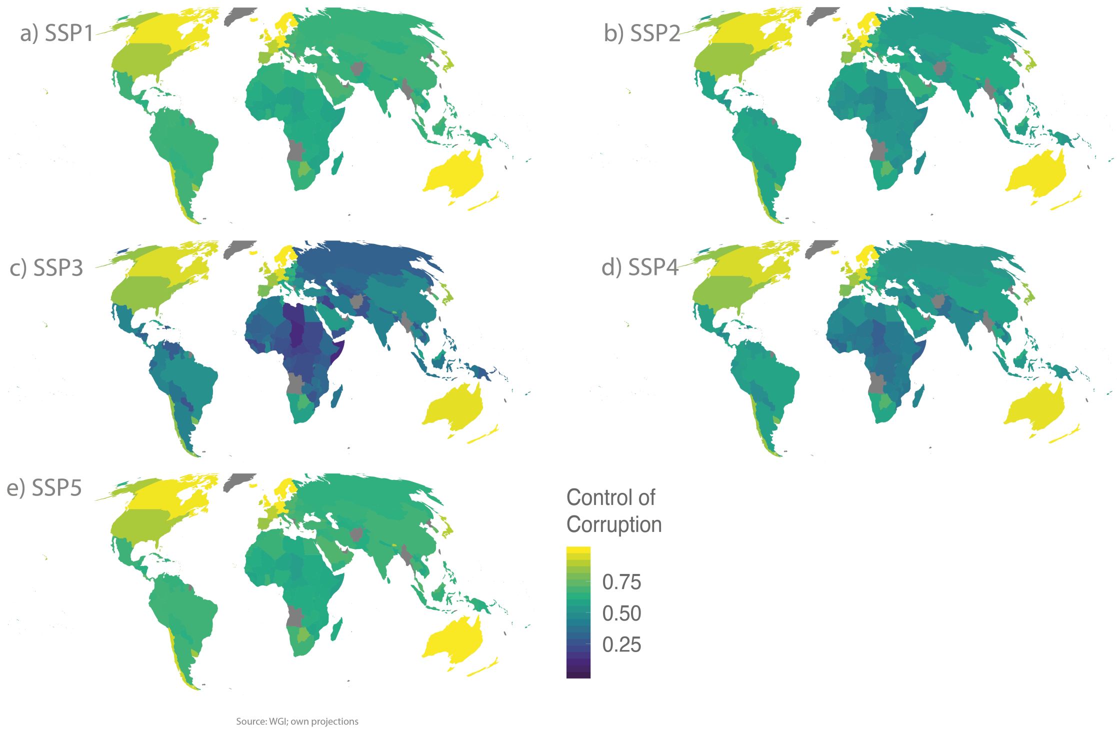

Figure A.5: Projections of the WGI control of corruption component for 2100.

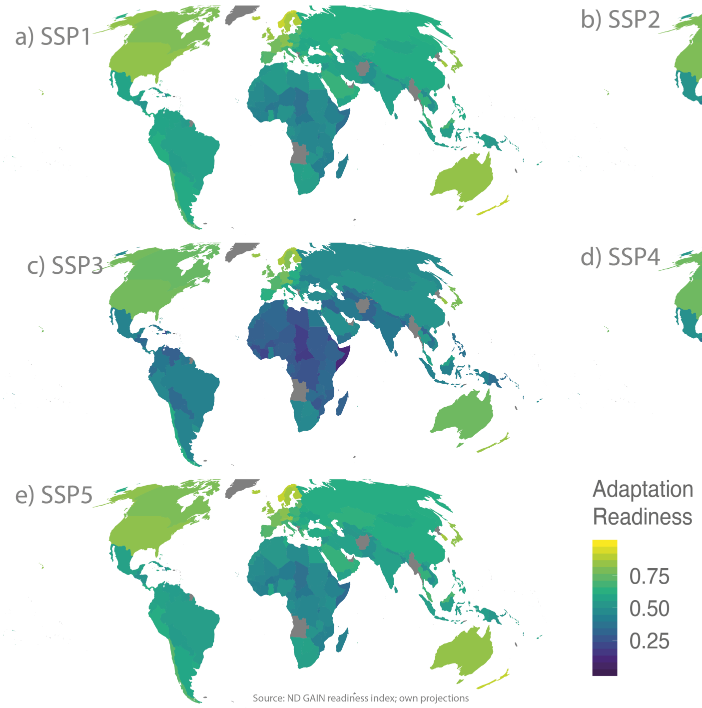

Figure A.6: Projections of the ND GAIN readiness component in 2050.

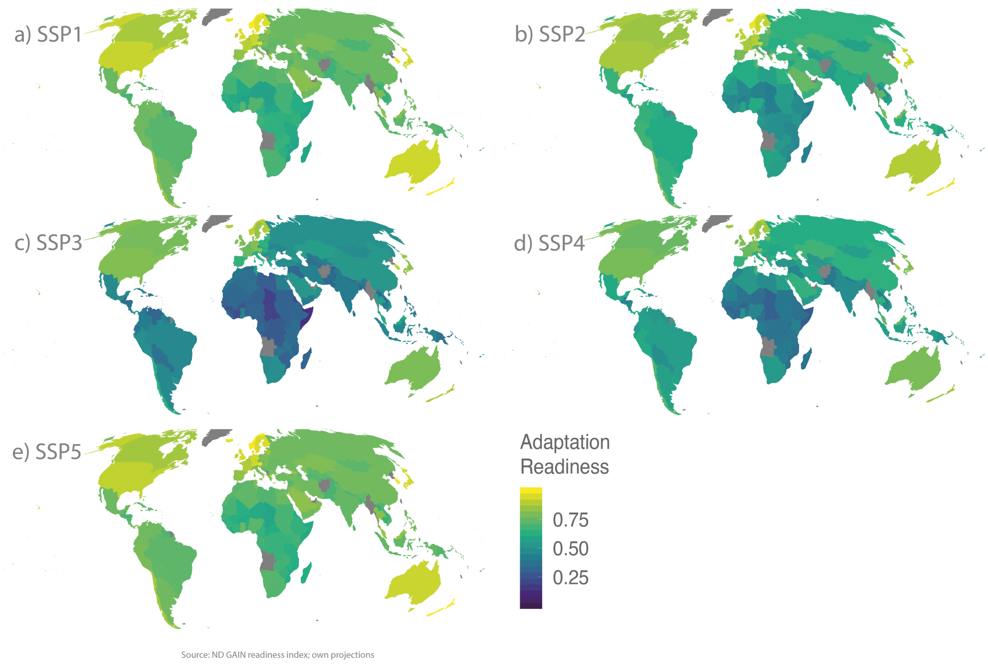

Figure A.7: Projections of the ND GAIN readiness component in 2100.

B

Appendix for Chapter 3: Overcoming gender inequality for climate resilient development

% Error: Argument ‘notes.append’ must be of type ‘logical’ (TRUE/FALSE)

B.1 Model validation

We assess the predictive ability of the variables used and the model employed using a simple validation exercise based on an out-of-sample predictive exercise. Using data spanning the period 2000-2005, we estimate an autoregressive model for our gender inequality variable, which serves as a benchmark to evaluate the (out-of-sample) predictive content of the information contained in the covariates of our specification. The autoregressive specification is given by

$$GII^*_{i,t} = \alpha_i + \vartheta GII^*_{i,t-5} + \varepsilon_{i,t},$$

implying that the dynamics of the gender inequality index can be explained by mean reverting dynamics around a country-specific equilibrium which is given by $\alpha_i/(1-\vartheta)$. Using this specification after estimating it for the period 2000-2005, we can obtain out-of-sample forecasts for all the countries in our sample for the year 2010. We also estimate a model that includes information about GDP per capita, education and the education gap, the three driving factors of gender inequality we consider in our main specification,

$$GII^*_{i,t} = \alpha_i + \vartheta GII^*_{i,t-5} + \beta_1 \ln GDPpc_{i,t-5} + \beta_2 education_{i,t-5} + \beta_3 educationgap_{i,t-5} + \varepsilon_{i,t}$$

where the covariates enter with a lag of five years to allow for five years-ahead out-of-sample predictions. After estimating this specification for the period 2000-2005, we can obtain predictions of the gender inequality index in 2010 for the countries in our sample based on a model that includes information on income and education dynamics. Expanding the set of in-sample observations to 2000-2006, we can obtain out-of-sample predictions for the year 2011 and repeating this exercise by expanding the sample used to estimate the model we can obtain 1202 five years-ahead forecasts spanning the period 2010-2017.

	AR	MODEL
RMSFE	0.306	0.283
DA	56.32%	68.64%
DV	0.152	0.207
Obs.	1202	1202

Table B.1: Out-of-sample validation exercise, model vs. benchmark AR specification

Supplementary Table 2 presents several standard measures of predictive error for the autoregressive (AR) specification and our model (MODEL) based on these forecasts. We compute (i) the mean squared forecast error (MSFE), which is the average of the squared deviations between realized and forecast values; (ii) the directional accuracy (DA) statistic, which gives the percentage of out-of-sample observations whose direction of change (increase or decrease) was correctly predicted, and (iii) the directional value (DV), which gives the average absolute value of the correctly predicted changes and should inform about whether the corresponding model fails at forecasting important changes in the target variable.

The results of the validation exercise based on the out-of-sample predictive ability of the model used give clear evidence that the covariates used in the model contain predictive information about future changes in the gender inequality index. In addition to reducing MSFE, the use of variables related to income, education and its distribution across genders increases directional accuracy very substantially, from around 56% correctly predicted changes to almost 69%. In addition, the changes which are forecast correctly are on average larger than those in the benchmark specification.

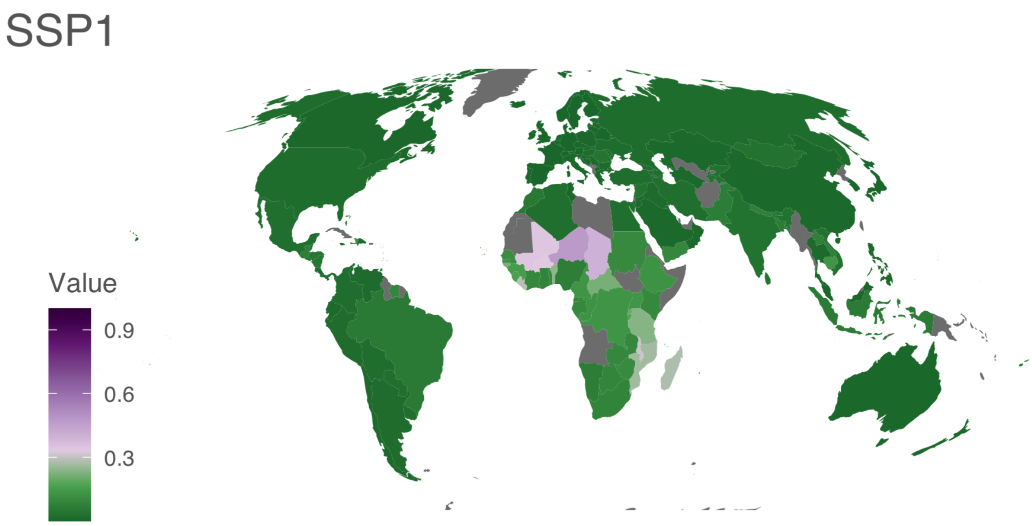

Figure B.1: GII projections for all SSPs in 2050

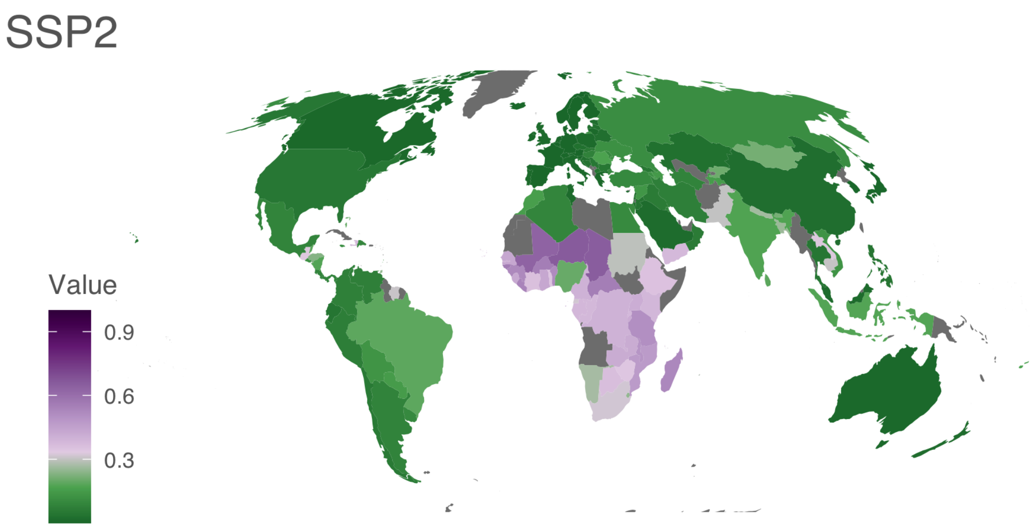

Figure B.2: GII projections for all SSPs in 2050

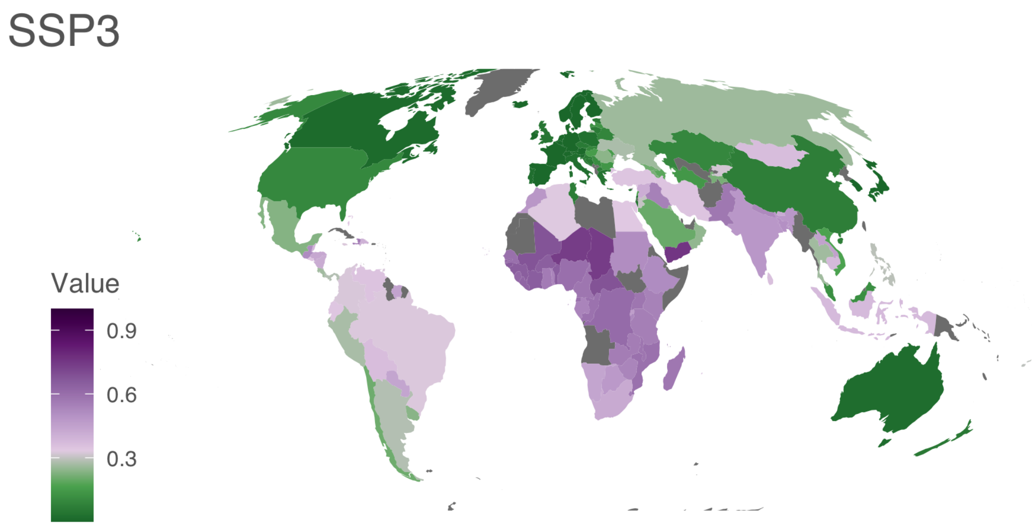

Figure B.3: GII projections for all SSPs in 2050

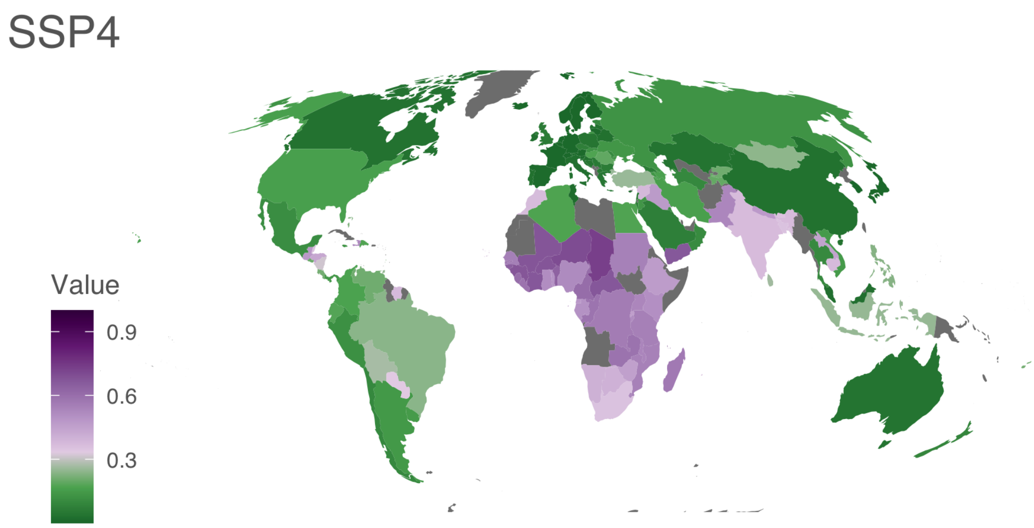

Figure B.4: GII projections for all SSPs in 2050

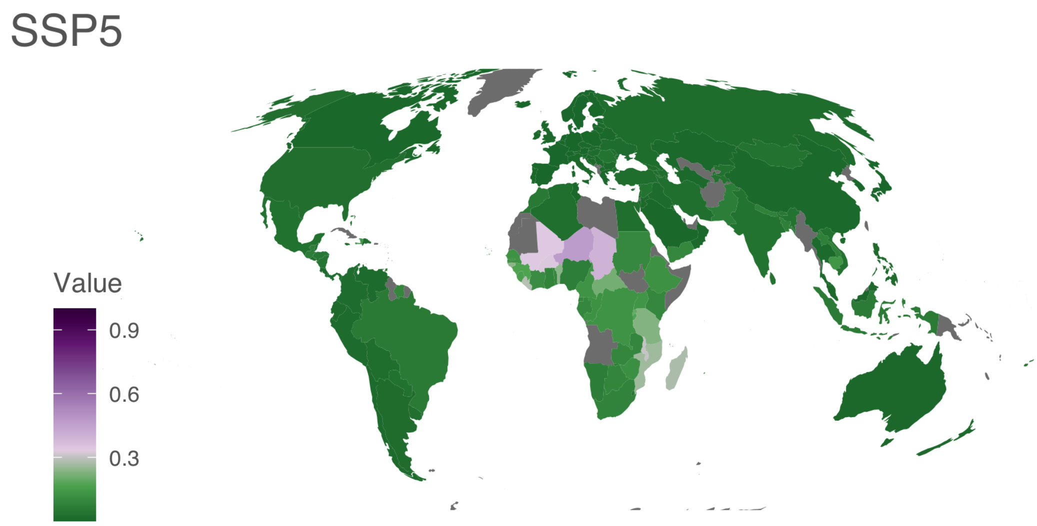

Figure B.5: GII projections for all SSPs in 2050

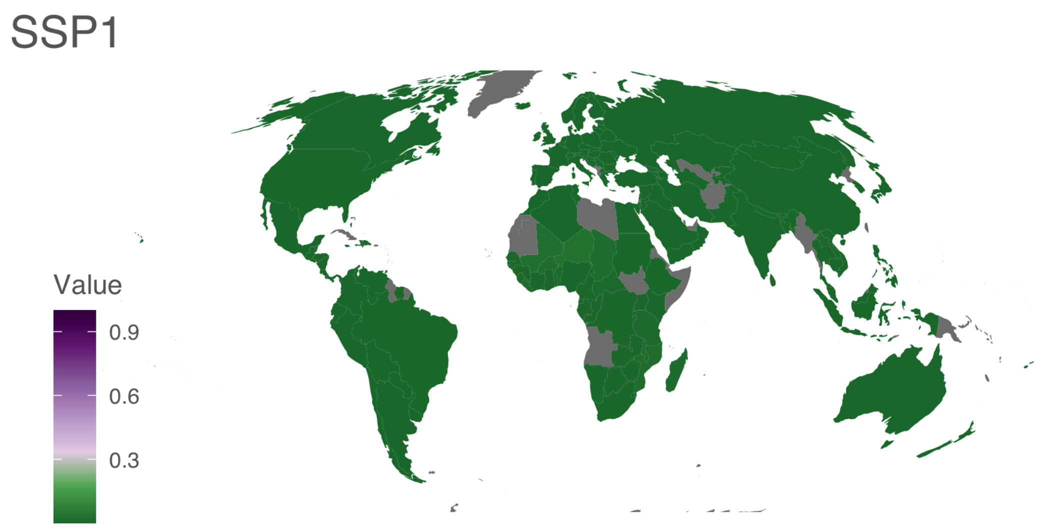

Figure B.6: GII projections for all SSPs in 2100

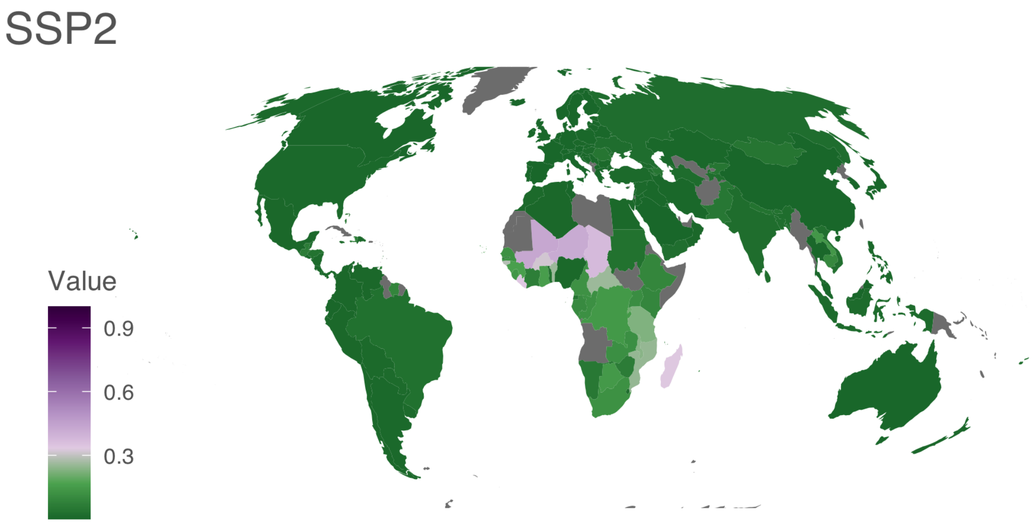

Figure B.7: GII projections for all SSPs in 2100

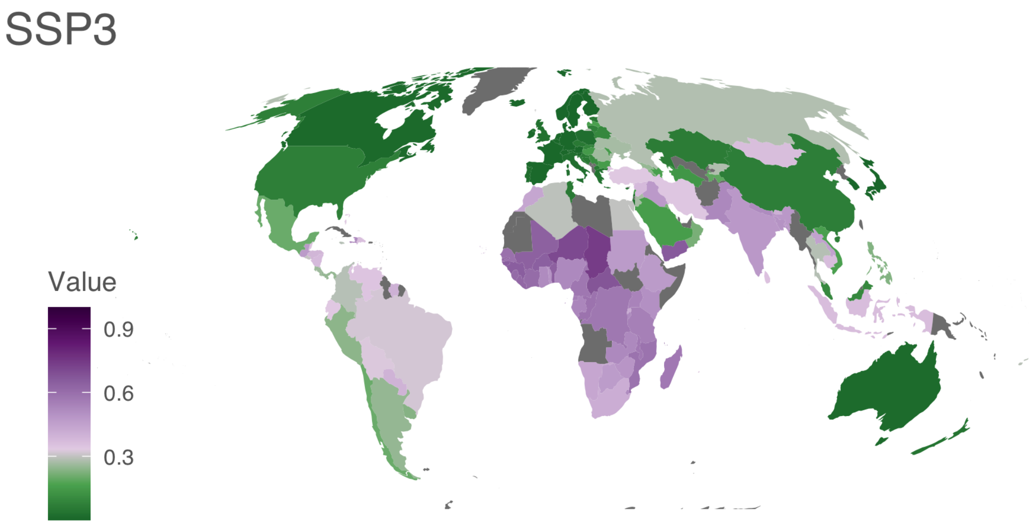

Figure B.8: GII projections for all SSPs in 2100

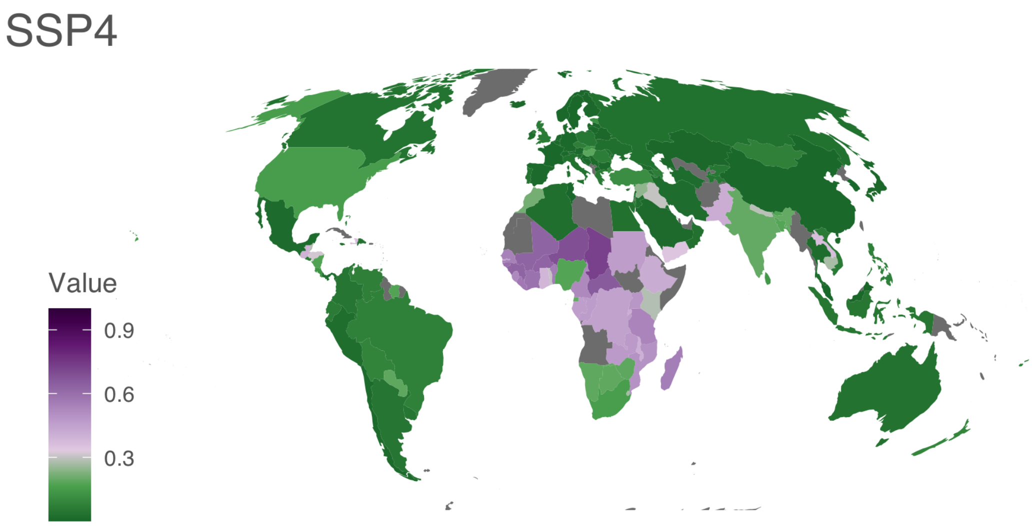

Figure B.9: GII projections for all SSPs in 2100

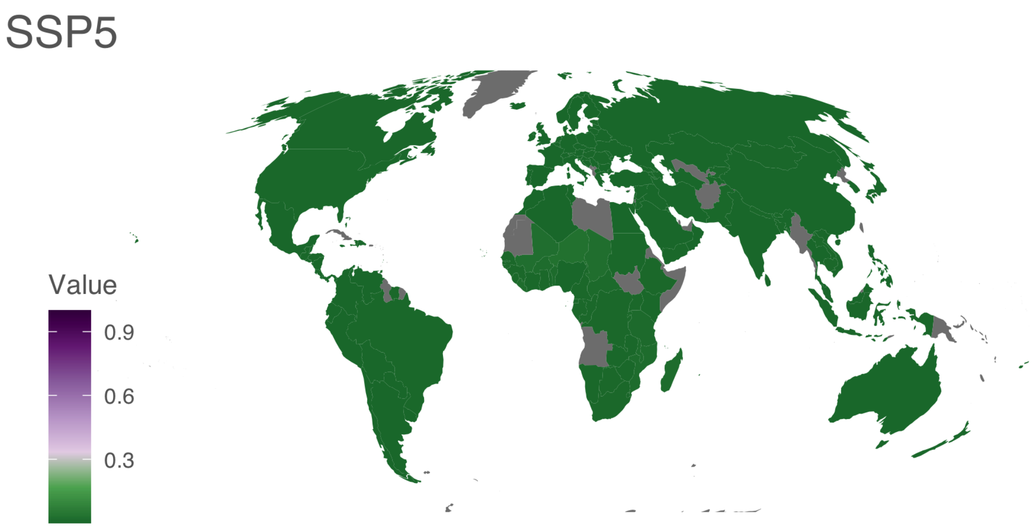

Figure B.10: GII projections for all SSPs in 2100

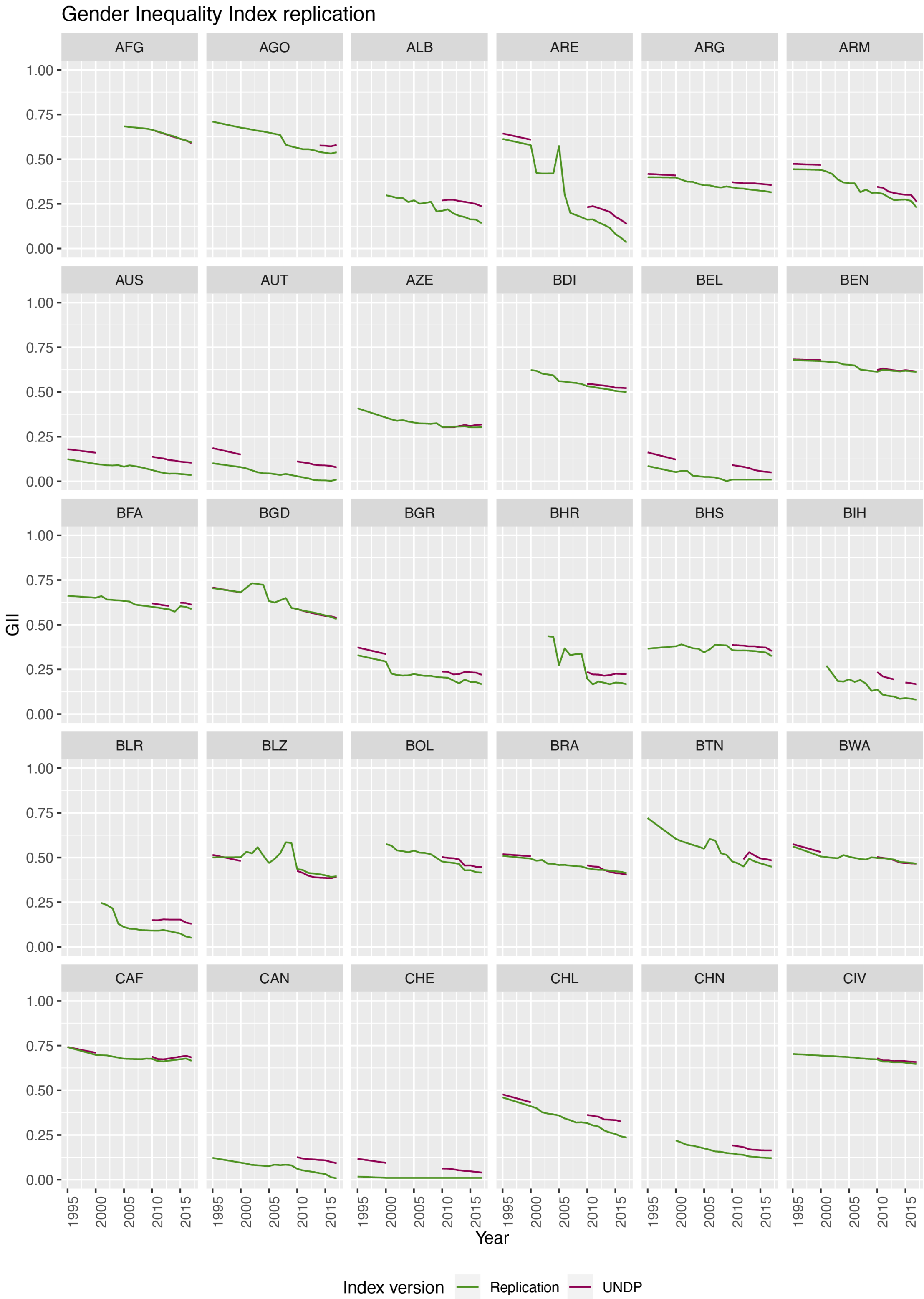

Figure B.11: GII reconstruction validation. Timeseries of the Gender Inequality Index (GII). The figure shows country-level values for the original index calculated by the UNDP and the authors' replication of the method.

Figure B.12: GII reconstruction validation. Timeseries of the Gender Inequality Index (GII). The figure shows country-level values for the original index calculated by the UNDP and the authors' replication of the method.

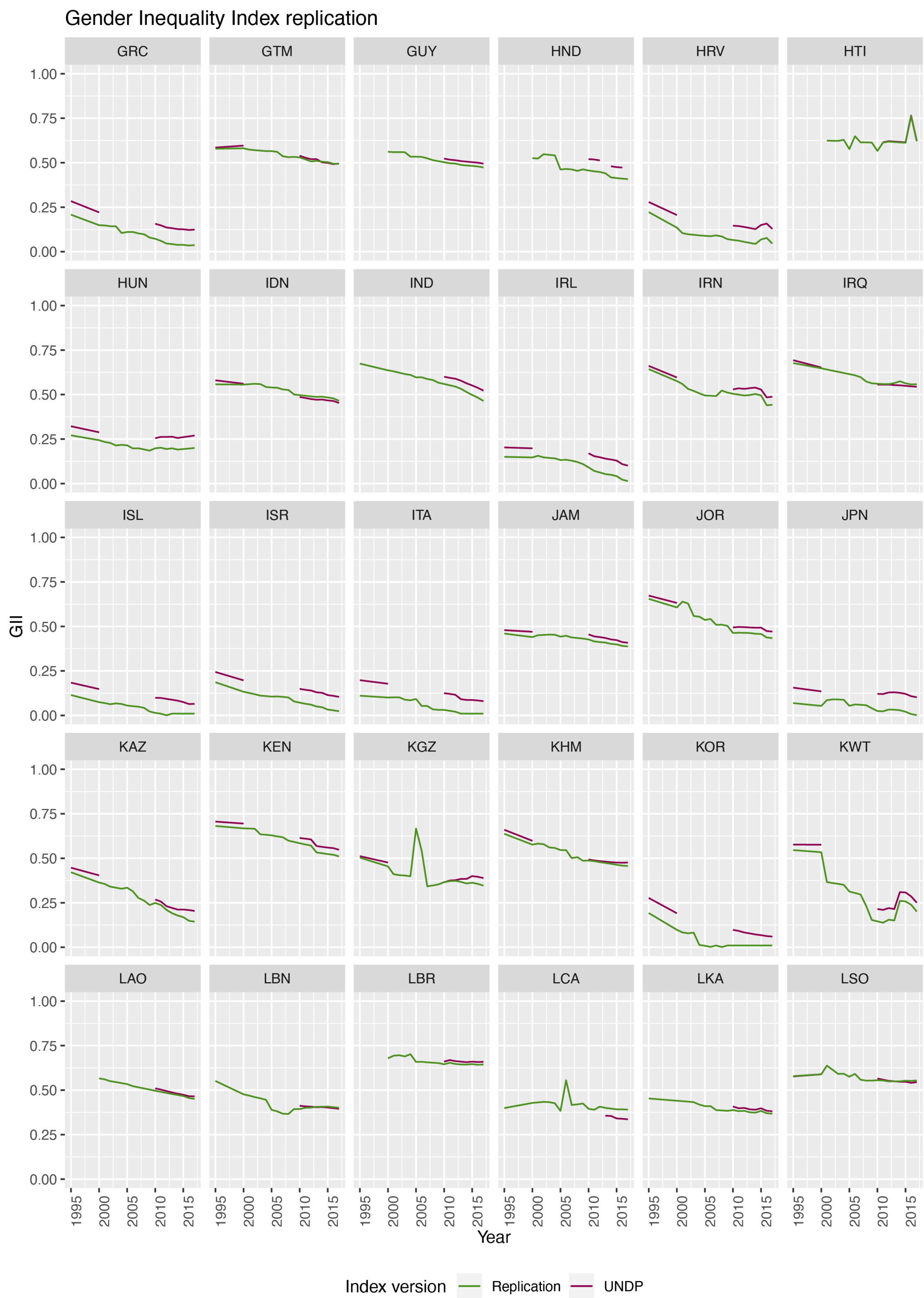

Figure B.13: GII reconstruction validation. Timeseries of the Gender Inequality Index (GII). The figure shows country-level values for the original index calculated by the UNDP and the authors' replication of the method.

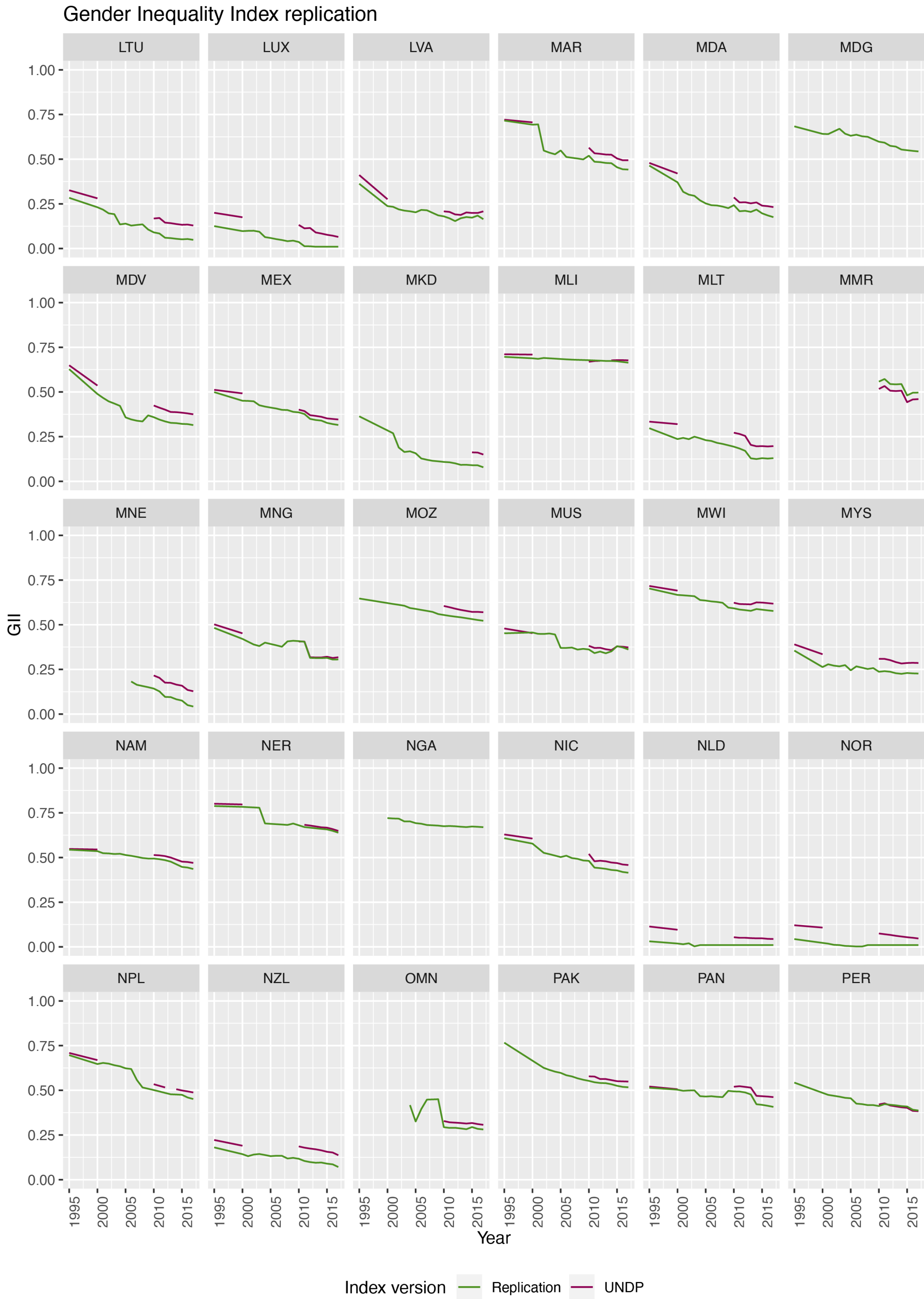

Figure B.14: GII reconstruction validation. Timeseries of the Gender Inequality Index (GII). The figure shows country-level values for the original index calculated by the UNDP and the authors' replication of the method.

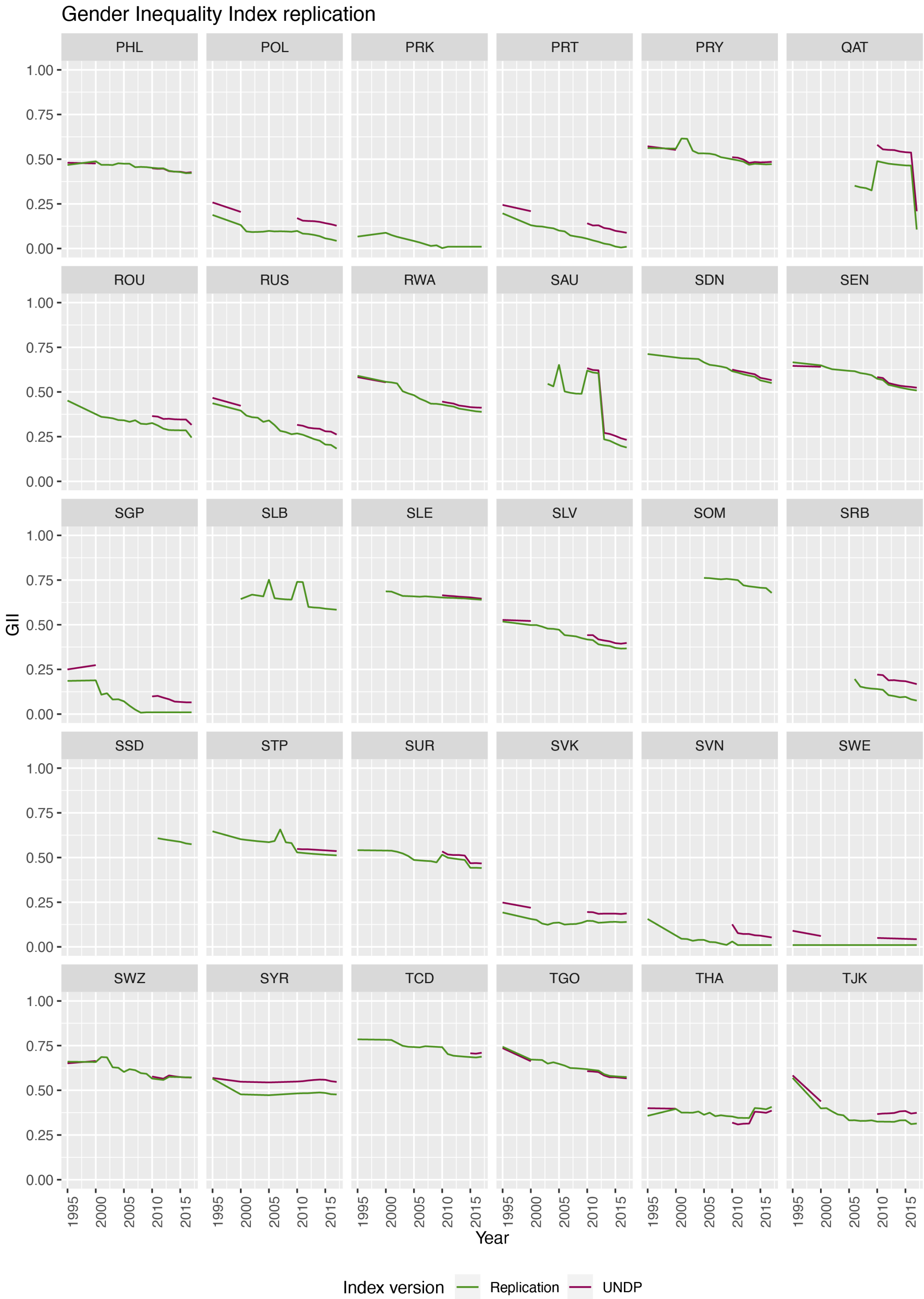

Figure B.15: GII reconstruction validation. Timeseries of the Gender Inequality Index (GII). The figure shows country-level values for the original index calculated by the UNDP and the authors' replication of the method.

C

Appendix for Chapter 4: Future cooling gap in Shared Socioeconomic Pathways

C.1 Shared Socioeconomic Pathways (SSPs)

Shared Socioeconomic Pathways provide a scenario space to explore the range of possible changes in socioeconomic conditions over the next century. They can be thought of as "what-if" scenarios of implications of the socioeconomic parameters for challenges to climate change adaptation and mitigation. SSPs quantify five different narratives of socioeconomic futures to operationalize them for climate change research (O'Neill, Kriegler, et al. 2017). They are a widely used tool in the climate research community, indispensable for integrated assessments of the dynamics between socioeconomic and climate change variables and are also the scenario framework used in the Sixth Assessment report of the Intergovernmental Panel on Climate Change (IPCC).

SSP1, the 'sustainability' scenario, is characterized by low challenges to mitigation and adaptation, a result of increased investments in education, health, renewable energy sources and declining inequalities between and within countries, thus limiting impacts and increasing adaptive capacity. SSP2, the 'middle of the road' scenario, maintains premediated challenges to adaptation and mitigation, and is a pathway of uneven and slower socioeconomic progress, compatible with the continuation of historical trends. SSP3 is characterized by high challenges to both mitigation and adaptation, which are a product of a growing divergence between economies, weak international cooperation and increase in internal and international conflicts. SSP4, the scenario of 'inequality', leads to low challenges for mitigation, due to technological advancements in high income countries, but high challenges for adaptation, because of an unequal distribution of advancements and resources across countries. Finally, SSP5 is similar to SSP1 in the fast socioeconomic progress on all fronts, but with the major difference of the progress being powered by fossil fuels, which produces substantially higher emissions and resulting climate impacts but assumes low adaptation challenges because of high socioeconomic development.

C.2 Representative Concentration Pathways (RCPs)

RCPs are scenarios of future greenhouse gas emissions and air pollutants – and therefore of future warming – which are used as inputs to climate models and for assessment of future climate impacts. They are used in conjunction with the SSP scenarios which show the socioeconomic component of the future pathways.

C.3 Climate maximum saturation

The climate parameter (climate maximum saturation) defines the level of AC ownership only as a function of the CDDs, if unconstrained by income (i.e. everyone who needs AC can afford one). We use the parametrization of the relationship between climate maximum saturation and CDDs from McNeil and Letschert (2007). They derived the functional relationship on the sample of census divisions in the United States (New England, Middle Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain North, Mountain South Pacific), under the assumption that they span many different climatic zones, but that AC ownership is largely unconstrained by income.

The relationship between climate maximum saturation and CDDs is found to be an logarithmic function (McNeil and Letschert 2008; Isaac and van Vuuren 2009), i.e. the need for AC increases rapidly with growing degree days, but tapers off as it reaches. The set point temperature for which CDDs are calculated is based on the estimate of the temperature at which the energy use is at the minimum (neither cooling nor heating). In previous studies, CDDs were routinely calculated with the set point temperature of 18°C which is the estimate based on the minimum energy use in the US and Europe (Isaac and van Vuuren 2009). Set point temperature reflects preferences for indoor temperature, which are a result of different factors such as thermal history (longer term experience with pervious thermal conditions) and thermal comfort zone (Jowkar et al. 2020), lifestyle factors (Fabi et al. 2013), and infrastructural factors such as prevalent building characteristics (De Cian et al. 2019).

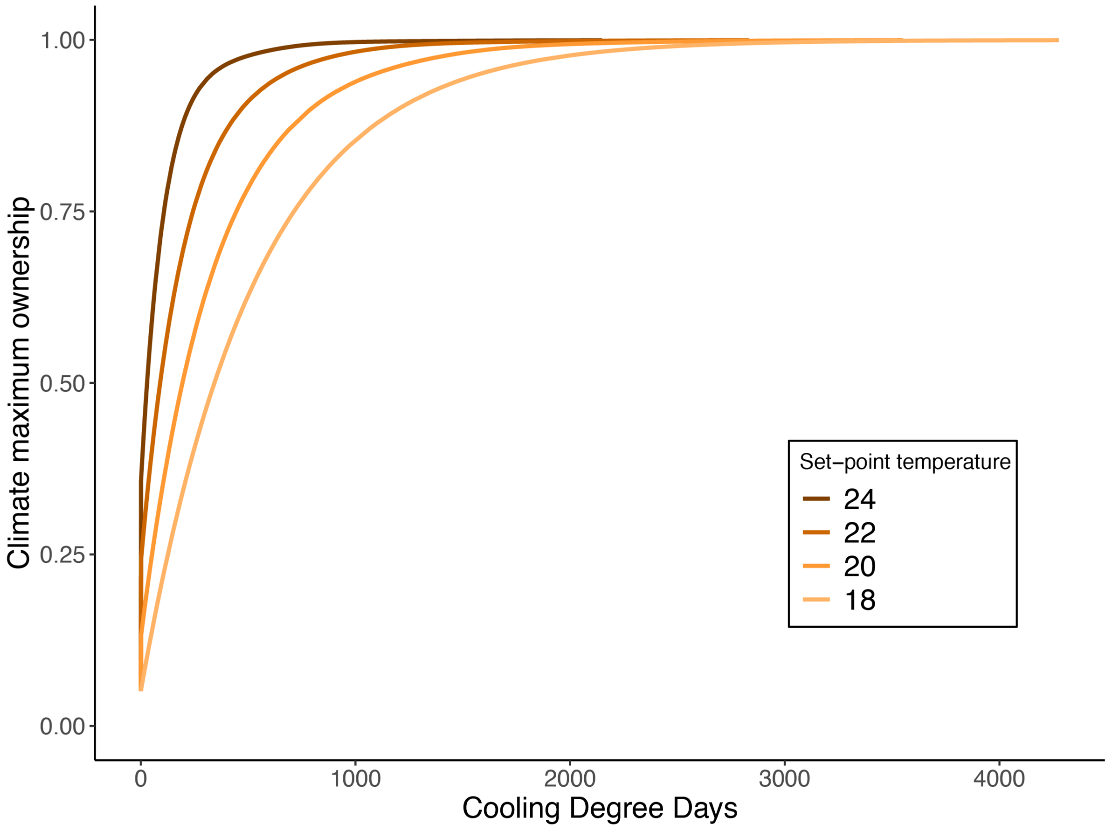

Figure C.1: Climate maximum saturation for different set point temperatures.

Since these factors that influence thermal comfort vary around the world, and here we use a sample with countries beyond the US and Europe, we analyze the AC ownership for the set point temperature thresholds of 18°C, 20°C, 22°C and 24°C. For orientation, Argentina would currently have 898 (162) population weighted CDDs with the set point temperature of 18°C (24°C), Italy would have 654 (116), Nigeria 3356 (1391), or the United States 956 (254).

We adjust the climate maximum saturation curves for the different set point temperatures to make the model more contextually relevant. To do so, we fit a spline function to the relationship between CDDs for 18°C and each of the other four set point temperatures we show here. We then use the coefficient estimate for the temperature-specific covariate to calculate CDD18 equivalents for other set point temperatures and calculate their respective climate maximum saturation curves as shown on Supplementary Figure 1.

For future projections of Climate Maximum Saturation, we use CDDs in three scenarios of future greenhouse gas emissions – the Representative Concentration Pathways (RCPs): 2.6, 4.5 and 6.0.

Table C.1: Regression results

	Dependent variable:		
	Air conditioning availability		
	(1)	(2)	(3)
GDP per capita	0.0001***	0.0001***	0.0001***
	(0.00001)	(0.00001)	(0.00001)
Inequality		−0.044***	−0.055***
		(0.017)	(0.017)
Urbanization			0.015**
			(0.007)
Constant	−1.762***	−0.055	−0.345
	(0.179)	(0.673)	(0.688)
Observations	67	67	67
R^2	0.629	0.665	0.695
Log Likelihood	57.083	60.215	62.386
Note:			*p<0.1; **p<0.05; ***p<0.01

Table C.2: Regional classification of countries

Country	Region
Armenia	Central Asia
Azerbaijan	Central Asia
Kazakhstan	Central Asia
Kyrgyzstan	Central Asia
Russia	Central Asia
Tajikistan	Central Asia
Turkey	Central Asia
Turkmenistan	Central Asia
Australia	East Asia & Pacific
China	East Asia & Pacific
Fiji	East Asia & Pacific
Indonesia	East Asia & Pacific
Japan	East Asia & Pacific
South Korea	East Asia & Pacific
Laos	East Asia & Pacific
Myanmar (Burma)	East Asia & Pacific

Table C.2: Regional classification of countries *(continued)*

Country	Region
Thailand	East Asia & Pacific
Vietnam	East Asia & Pacific
Albania	Europe
Bosnia & Herzegovina	Europe
France	Europe
Italy	Europe
Montenegro	Europe
Netherlands	Europe
North Macedonia	Europe
Serbia	Europe
Spain	Europe
Sweden	Europe
Ukraine	Europe
Argentina	Latin America & Caribbean
Barbados	Latin America & Caribbean
Belize	Latin America & Caribbean
Brazil	Latin America & Caribbean
Chile	Latin America & Caribbean
Colombia	Latin America & Caribbean
Dominican Republic	Latin America & Caribbean
El Salvador	Latin America & Caribbean
Guyana	Latin America & Caribbean
Honduras	Latin America & Caribbean
Jamaica	Latin America & Caribbean
Mexico	Latin America & Caribbean
St. Lucia	Latin America & Caribbean
Trinidad & Tobago	Latin America & Caribbean
Uruguay	Latin America & Caribbean
Algeria	Middle East & North Africa
Egypt	Middle East & North Africa
Iran	Middle East & North Africa
Iraq	Middle East & North Africa
Jordan	Middle East & North Africa
Saudi Arabia	Middle East & North Africa
Tunisia	Middle East & North Africa
Palestinian Territories	Middle East & North Africa
Yemen	Middle East & North Africa
Canada	North America
United States	North America
Bangladesh	South Asia
India	South Asia

Table C.2: Regional classification of countries *(continued)*

Country	Region
Maldives	South Asia
Pakistan	South Asia
Angola	Sub-Saharan Africa
Burkina Faso	Sub-Saharan Africa
Cameroon	Sub-Saharan Africa
Central African Republic	Sub-Saharan Africa
Congo - Brazzaville	Sub-Saharan Africa
Côte d'Ivoire	Sub-Saharan Africa
Ethiopia	Sub-Saharan Africa
Gabon	Sub-Saharan Africa
Gambia	Sub-Saharan Africa
Ghana	Sub-Saharan Africa
Guinea-Bissau	Sub-Saharan Africa
Mali	Sub-Saharan Africa
Niger	Sub-Saharan Africa
Nigeria	Sub-Saharan Africa
Senegal	Sub-Saharan Africa
South Africa	Sub-Saharan Africa
South Sudan	Sub-Saharan Africa
Sudan	Sub-Saharan Africa

Table C.3: Fitted vs observed values

ISO3	Observed AC availability	Fitted AC availabiliy	Residual (availability)	Climate maximum saturation	Observed AC ownership	Fitted AC ownereship	Residual (ownership)
ARG	39.3	34.6	-4.7	0.8	31.0	27.5	3.6
ARM	30.3	21.4	-8.9	0.4	11.1	7.9	3.2
AUS	99.3	96.2	-3.0	0.7	75.0	70.5	4.5
AZE	46.3	34.7	-11.6	0.7	33.3	25.0	8.3
BFA	1.3	8.4	7.2	1.0	0.5	8.4	-7.9
BGD	1.2	7.3	6.2	1.0	0.4	7.3	-6.8
BIH	8.1	18.8	10.7	0.3	2.5	6.4	-3.8
BRA	8.9	18.3	9.4	1.0	8.0	17.7	-9.7
CAF	1.0	3.8	2.8	1.0	0.2	3.7	-3.5
CAN	99.3	93.3	-6.0	0.3	48.0	32.1	15.9
CHL	17.0	28.0	11.0	0.1	0.8	1.4	-0.6
CHN	50.3	18.2	-32.1	0.8	41.3	15.0	26.4
CIV	2.4	7.4	4.9	1.0	1.7	7.3	-5.6
CMR	2.0	11.8	9.8	1.0	1.3	11.6	-10.3

Table C.3: Fitted vs observed values *(continued)*

ISO3	Observed AC availability	Fitted AC availabiliy	Residual (availability)	Climate maximum saturation	Observed AC ownership	Fitted AC ownereship	Residual (ownership)
COG	13.1	13.3	0.1	1.0	12.4	13.1	-0.7
COL	2.4	12.3	9.9	1.0	1.6	11.8	-10.2
DOM	8.7	14.9	6.2	1.0	7.9	14.5	-6.6
DZA	49.7	36.5	-13.2	0.8	41.2	30.2	10.9
EGY	4.4	15.9	11.5	1.0	3.6	15.2	-11.6
ESP	82.9	75.1	-7.8	0.6	54.0	48.6	5.4
ETH	1.5	9.7	8.2	0.8	0.6	7.9	-7.3
FJI	4.4	15.7	11.4	1.0	3.6	15.3	-11.7
FRA	45.9	87.4	41.5	0.3	14.0	26.7	-12.7
GAB	12.5	26.9	14.5	1.0	11.8	26.6	-14.9
GHA	1.6	10.0	8.4	1.0	0.8	10.0	-9.1
GMB	1.9	10.7	8.8	1.0	1.2	10.6	-9.5
GNB	1.5	5.3	3.8	1.0	0.8	5.3	-4.5
GUY	2.5	12.1	9.6	1.0	1.8	12.1	-10.2
HND	5.9	6.2	0.3	1.0	5.1	6.0	-0.9
IDN	9.6	14.7	5.1	1.0	9.0	14.7	-5.7
IND	18.5	13.1	-5.4	1.0	17.9	13.0	4.9
IRN	2.6	19.4	16.9	0.9	1.7	17.7	-16.0
IRQ	40.1	31.8	-8.3	1.0	39.4	31.4	8.0
ITA	70.2	78.9	8.7	0.5	36.6	40.9	-4.3
JAM	5.8	17.1	11.2	1.0	5.1	16.7	-11.7
JOR	11.2	26.1	14.8	0.9	9.7	23.7	-14.0
JPN	99.3	90.1	-9.2	0.7	91.0	65.3	25.7
KAZ	26.1	32.6	6.5	0.6	15.9	20.2	-4.3
KGZ	16.0	12.3	-3.7	0.3	5.3	4.2	1.1
KOR	96.0	73.1	-23.0	0.7	69.3	52.4	17.0
LAO	5.6	10.5	4.8	1.0	4.9	10.2	-5.4
MDV	17.8	18.4	0.6	1.0	17.3	18.4	-1.1
MEX	15.3	21.1	5.8	0.9	13.3	19.0	-5.7
MKD	79.7	18.1	-61.6	0.3	27.6	6.2	21.4
MLI	1.6	10.7	9.1	1.0	0.9	10.7	-9.8
NER	1.5	7.6	6.1	1.0	0.8	7.6	-6.9
NGA	2.8	8.6	5.8	1.0	2.1	8.6	-6.5
NLD	99.3	96.7	-2.6	0.1	11.0	4.9	6.1
PAK	15.2	16.0	0.8	1.0	14.5	15.8	-1.3
RUS	29.8	36.0	6.2	0.3	9.1	11.1	-2.0
SAU	63.3	41.8	-21.5	1.0	63.0	41.5	21.5

Table C.3: Fitted vs observed values *(continued)*

ISO3	Observed AC availability	Fitted AC availabiliy	Residual (availability)	Climate maximum saturation	Observed AC ownership	Fitted AC ownereship	Residual (ownership)
SDN	4.8	6.8	2.0	1.0	4.1	6.8	-2.7
SEN	2.6	10.7	8.0	1.0	1.9	10.6	-8.7
SLV	2.5	13.3	10.8	1.0	1.8	13.0	-11.3
SRB	19.5	22.7	3.2	0.4	8.2	9.7	-1.6
SSD	0.8	5.2	4.4	1.0	0.1	5.2	-5.1
SWE	99.3	97.8	-1.5	0.1	20.0	5.0	15.0
THA	21.0	19.1	-1.8	1.0	20.5	19.1	1.4
TJK	17.4	15.7	-1.7	0.7	11.9	11.0	0.8
TUN	26.1	24.6	-1.6	0.9	22.7	21.7	1.1
TUR	19.6	27.7	8.0	0.6	11.7	16.8	-5.2
UKR	9.8	28.3	18.6	0.4	3.9	12.1	-8.2
URY	41.3	39.2	-2.1	0.7	28.7	27.4	1.3
USA	99.3	94.0	-5.3	0.8	87.8	76.8	11.0
VNM	5.2	10.2	5.0	1.0	4.5	10.1	-5.6
YEM	13.9	14.8	0.9	0.9	12.3	13.6	-1.3
ZAF	8.7	6.7	-2.1	0.7	6.0	4.9	1.1

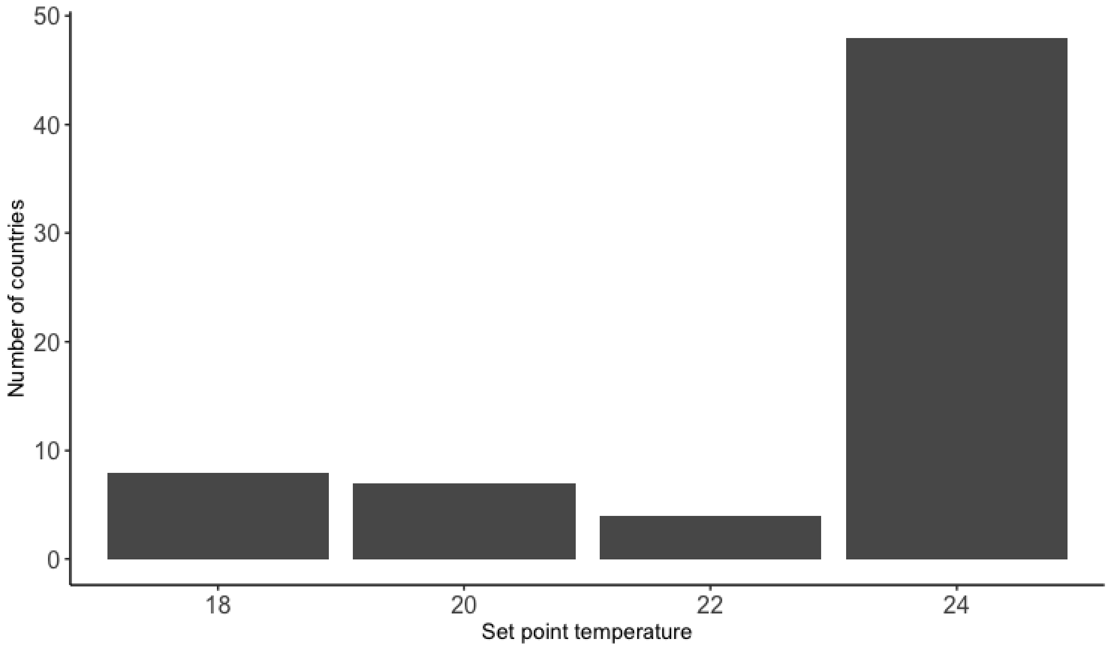

Figure C.2: Model selection based on the smallest residual.

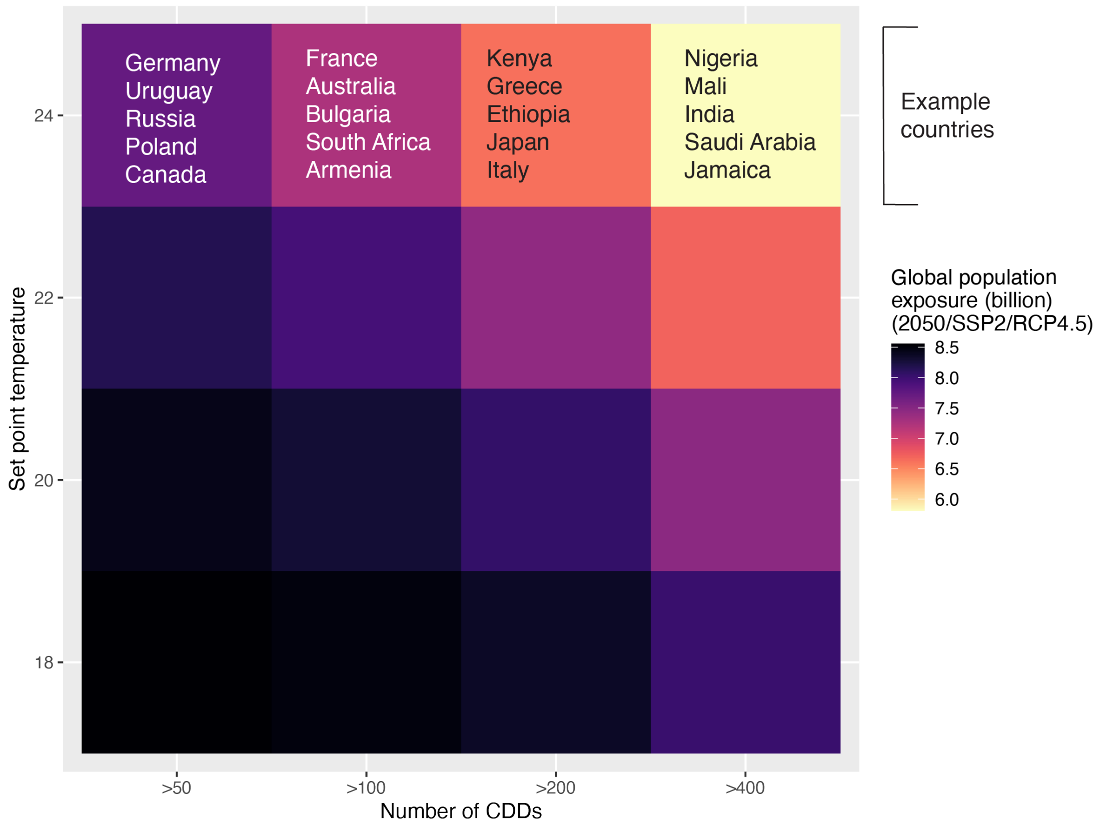

Figure C.3: Population exposure in different combinations of set point temperature and the count of CDDs. Estimates shown are for the socioeconomic scenario SSP2 and emissions scenario RCP 4.5.

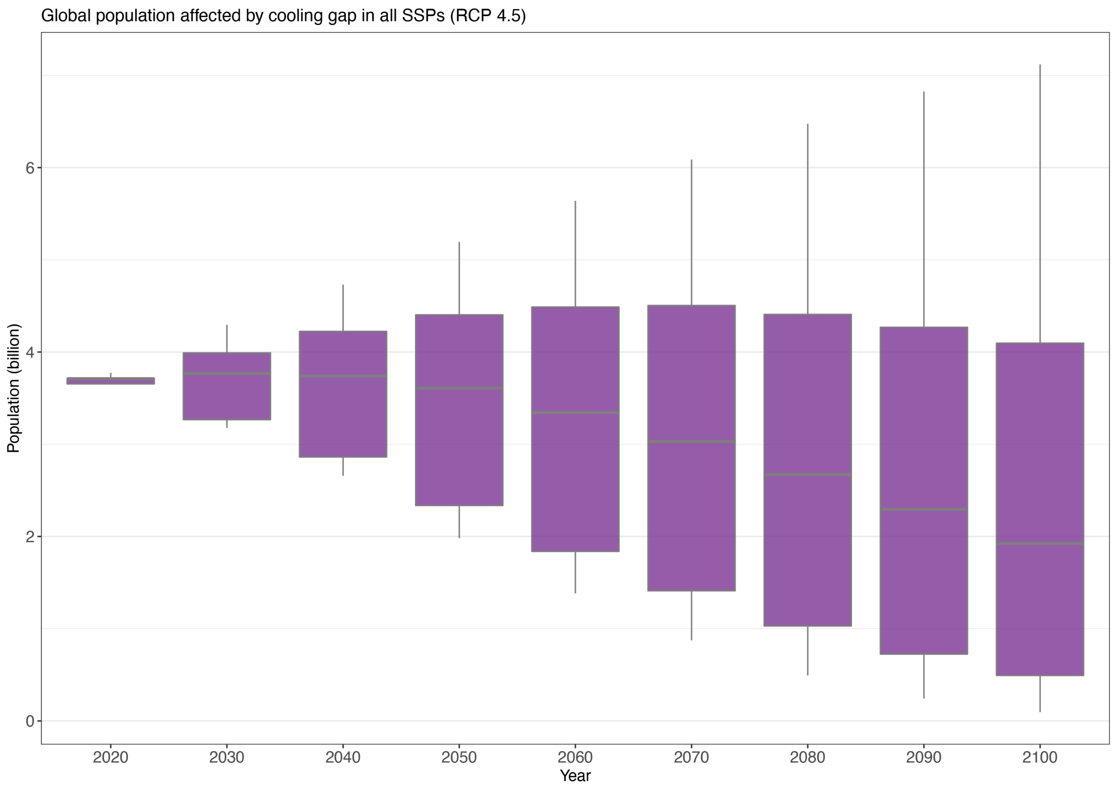

Figure C.4: Population affected by cooling gap across all socioeconomic scenarios (SSPs 1-5).

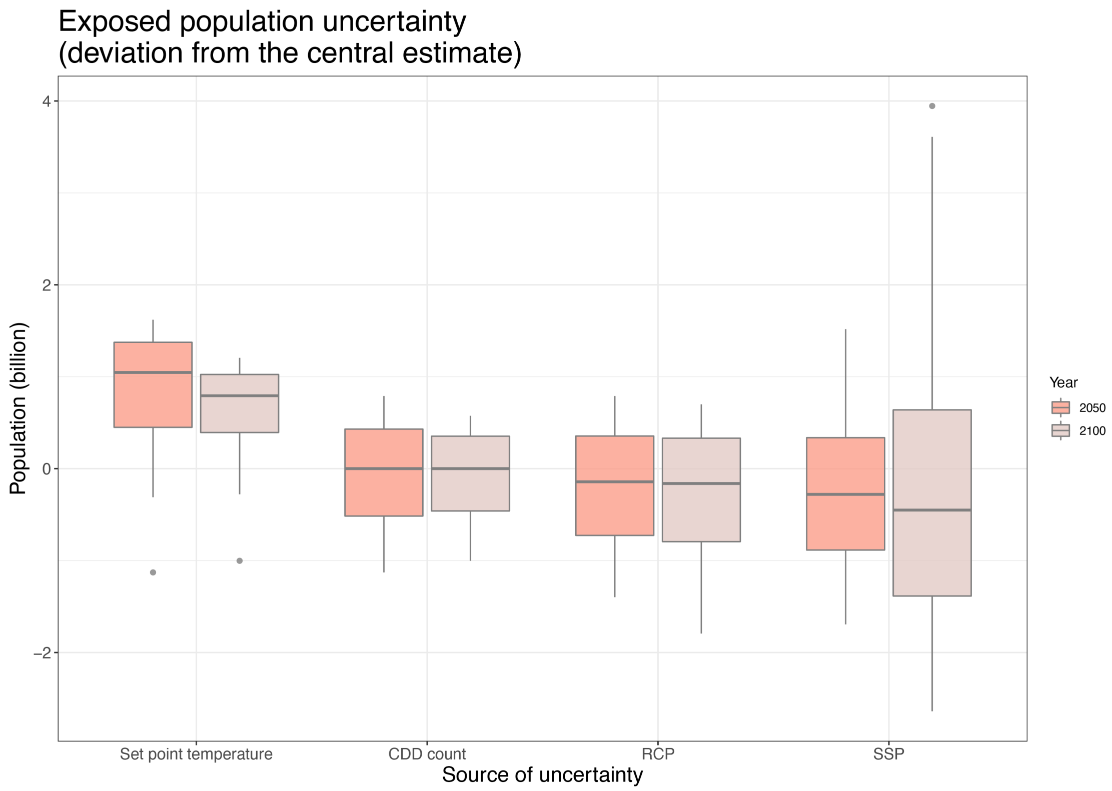

Figure C.5: Sources of uncertainty for exposed population, shown as a deviation from the central estimate (SSP2/RCP4.5 and median exposure for >50, >100, >200 and >400 CDDs above the set point temperature of 24oC).

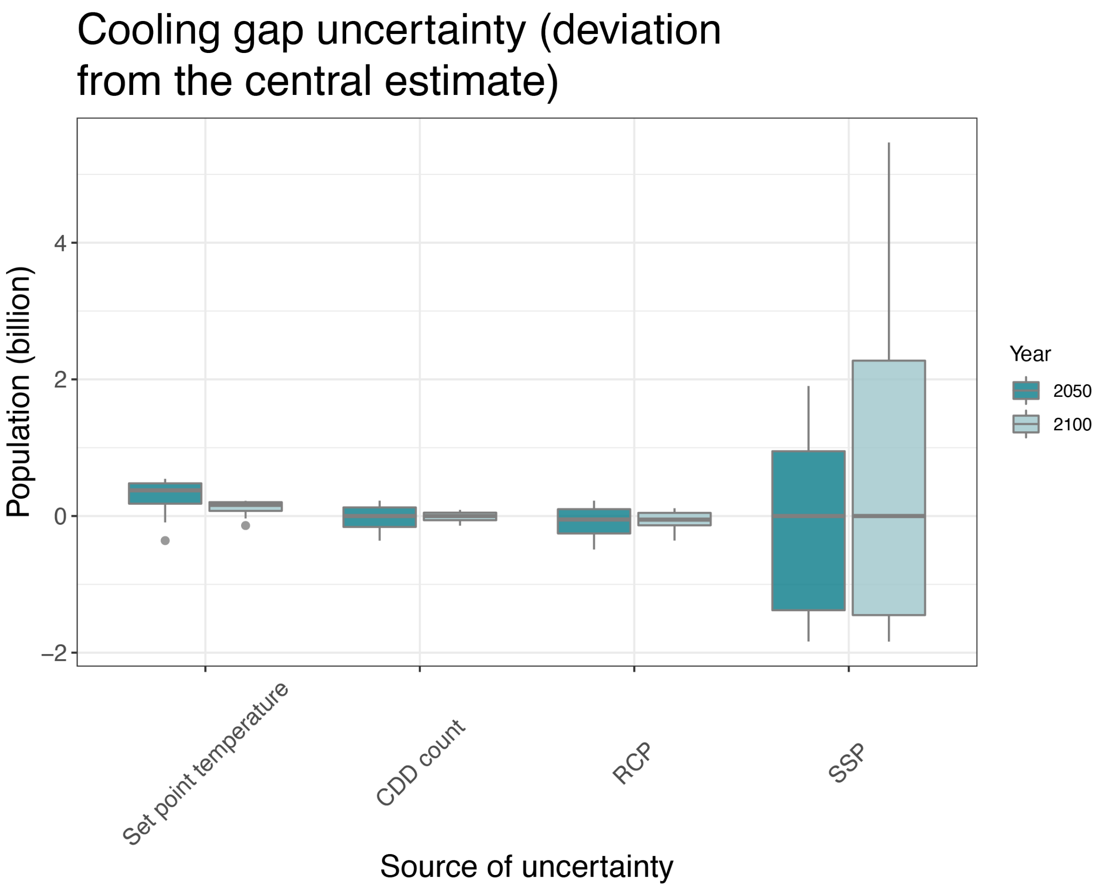

Figure C.6: Sources of uncertainty for population affected by cooling gap, shown as a deviation from the central estimate (SSP2/RCP4.5 and median exposure for >50, >100, >200 and >400 CDDs above the set point temperature of 24oC).

D

Appendix for Chapter 5: Scenarios of sustainable irrigation expansion in the 21st century

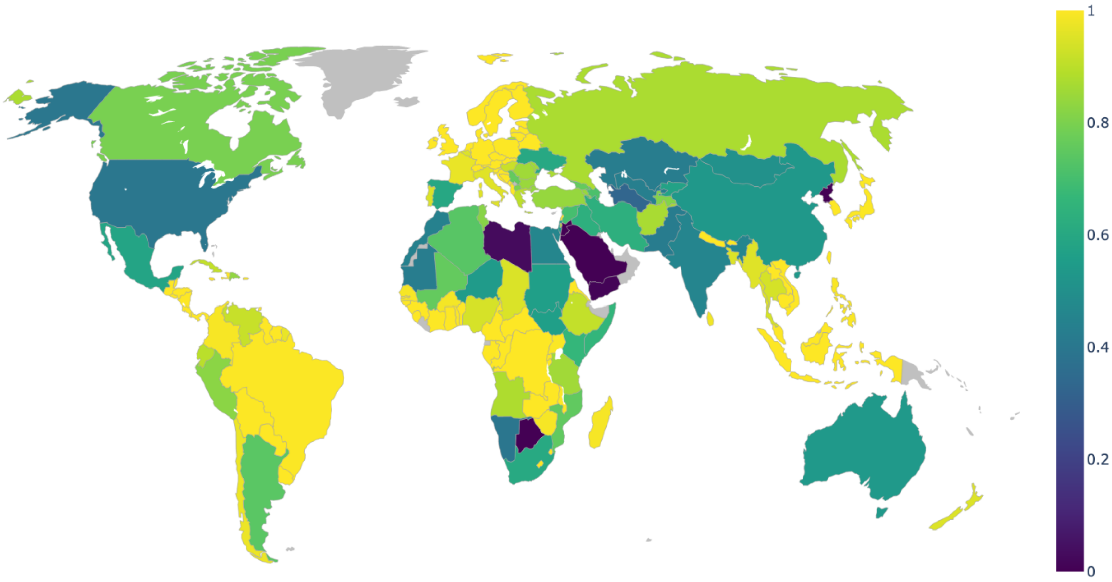

Figure D.1: Sustainable irrigation calorie production (2000). Fraction between the current sustainable irrigation calories produced compared to the total calories produced via irrigation. Derived from Rosa et al. (2018).

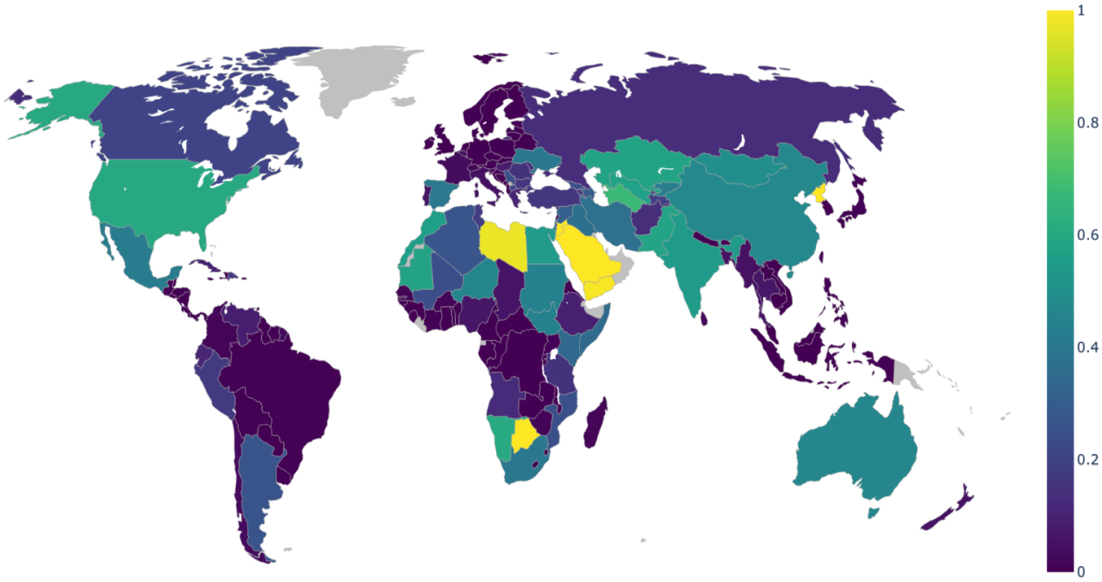

Figure D.2: Unsustainable calorie production (2000). Fraction between unsustainable calories produced via irrigation compared to the total irrigation calories produced. Derived from Rosa et al. (2018).

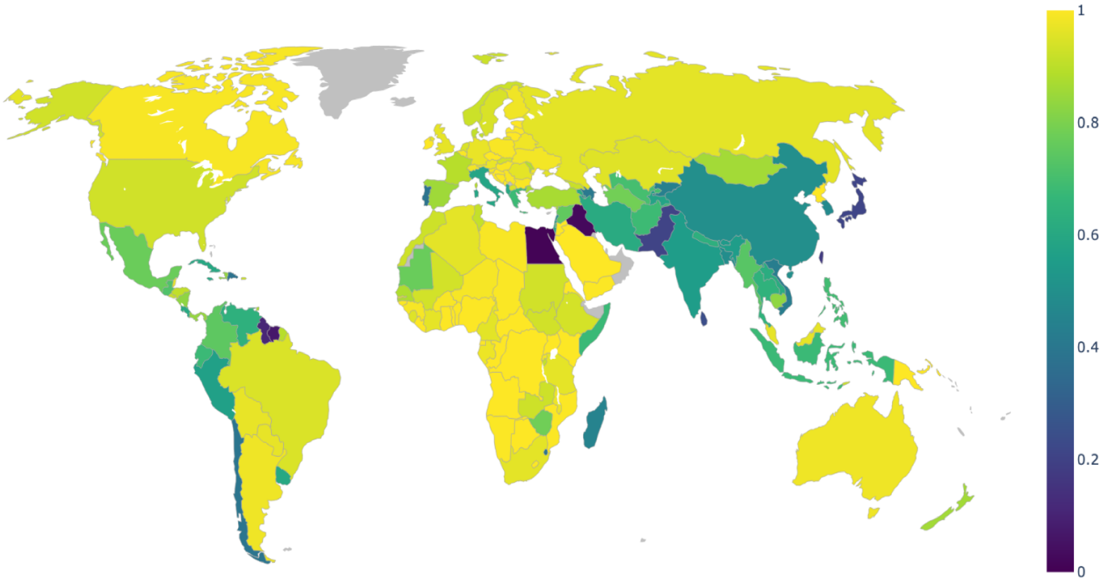

Figure D.3: Baseline share of rainfed crops in the total agricultural production. Derived from Rosa et al. (2018).

	CALORIES Irrigated (Rain-fed) (10^{15} per year)	PEOPLE Irrigated (Rain-fed) (billion per year)
	Current	
Sustainable	1.69	1.38
Unsustainable	1.19	0.97
Total current	2.88 (6.35)	2.36 (5.20)
	Additional at YGC	
Sustainable	3.38	2.77
Unsustainable	1.62	1.32
Total yield gap closure	7.88 (6.35)	6.46 (5.20)

Table D.1: Calorie production under current and yield gap closure scenarios. Sustainable irrigation is practiced in areas where blue water consumption (BWC) does not exceed renewable blue water availability (BWA), which accounts also for environmental flows. Irrigation is unsustainable when BWC >BWA (i.e., it sacrifices environmental flows, requires non-renewable groundwater resources, or inter-basin water transport. Adapted from Rosa et al. (2018).

Dependent Variable: SII					
Model	(1)	(2)	(3)	(4)	(5)
Share_rainfed	-0.865*** (0.054)	-0.863*** (0.049)	-0.878*** (0.049)	-0.866*** (0.050)	-0.870*** (0.050)
GDP		0.049*** (0.009)	0.021 (0.015)	0.021 (0.015)	0.005 (0.022)
Governance			0.228** (0.100)	0.229** (0.100)	0.245** (0.101)
Population				0.0001 (0.0001)	0.0001 (0.0001)
Urbanization					0.001 (0.001)
Constant	0.923*** (0.046)	0.506*** (0.087)	0.635*** (0.103)	0.619*** (0.104)	0.702*** (0.130)
Observations	138	138	138	138	138
R2	0.653	0.716	0.726	0.730	0.732
Adjusted R2	0.651	0.711	0.720	0.722	0.722
Residual Std. Error	0.148 (df = 136)	0.134 (df = 135)	0.132 (df = 134)	0.132 (df = 133)	0.132 (df = 132)
F Statistic	256.450*** (df = 1; 136)	169.914*** (df = 2; 135)	118.519*** (df = 3; 134)	89.809*** (df = 4; 133)	72.127*** (df = 5; 132)
Note: *p<0.1; **p<0.05; ***p<0.01					

Table D.2: Regression results

Region	2020_SSP2 (million)	2050_SSP2 (million)	2100_SSP2 (million)
Central Asia	96	127	156
East Asia & Pacific	592	674	739
Europe	103	122	139
Latin America & Caribbean	87	103	123
Midlle East & North Africa	50	57	63
North America	57	61	65
South Asia	327	371	414
Sub-Saharan Africa	34	70	109

Table D.3: Total amount of people fed per region via sustainable irrigation in 2020, 2050 and 2100 for SSP2. People fed were quantified assuming a calorie intake of 3343 kcal per capita per day8. The amount of people fed is recorded in million per year.

Region	2020_SSP3 (million)	2050_SSP3 (million)	2100_SSP3 (million)
Central Asia	93	110	12
East Asia & Pacific	588	639	661
Europe	102	115	125
Latin America & Caribbean	86	94	101
Midlle East & North Africa	50	53	55
North America	57	61	64
South Asia	321	343	355
Sub-Saharan Africa	30	46	63

Table D.4: Total amount of people fed per region via sustainable irrigation in 2020, 2050 and 2100 for SSP3. People fed were quantified assuming a calorie intake of 3343 kcal per capita per day8. The amount of people fed is recorded in million per year.

Region	2020_SSP4 (million)	2050_SSP4 (million)	2100_SSP4 (million)
Central Asia	96	126	152
East Asia & Pacific	591	669	724
Europe	103	122	138
Latin America & Caribbean	87	102	119
Midlle East & North Africa	50	55	61
North America	57	62	66
South Asia	323	355	379
Sub-Saharan Africa	32	51	73

Table D.5: Total amount of people fed per region via sustainable irrigation in 2020, 2050 and 2100 for SSP4. People fed were quantified assuming a calorie intake of 3343 kcal per capita per day. The amount of people fed is recorded in million per year.

Region	2020_SSP5 (million)	2050_SSP5 (million)	2100_SSP5 (million)
hline Central Asia	98	143	183
hline East Asia & Pacific	596	709	792
hline Europe	104	129	152
hline Latin America & Caribbean	88	114	140
hline Midlle East & North Africa	51	60	68
hline North America	58	63	70
hline South Asia	329	393	445
hline Sub-Saharan Africa	36	89	134
hline			

Table D.6: Total amount of people fed per region via sustainable irrigation in 2020, 2050 and 2100 for SSP5. People fed were quantified assuming a calorie intake of 3343 kcal per capita per day. The amount of people fed is recorded in million per year.

Scenario	People fed (billion per year)	Calories (kcal*10^{15} per year)
2000	1.4	1.7
Sustainable at YGC	3.9	4.9
2100 SSP1	1.9	2.3
2100 SSP2	1.8	2.2
2100 SSP3	1.5	1.9
2100 SSP4	1.7	2.1
2100 SSP5	2.0	2.4

Table D.7: Total people fed and calories produced globally for different scenarios. Global people fed in 2000 and Sustainable at YGC was quantified using data from Rosa et al (2018). Other projections for the end of the century were quantified using our projections and can also be derived from Tab.1 from the main text.

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